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NASA TN D-2289

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • APRIL 1964

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SUMMARY

During the altitude-buildup program with the X-15 airplane, flights were made in which the boost-climbout phase was similar to the launch of the initial stage of multistage vehicles. The pilot's performance is analyzed in an attempt to better define the human pilot's capability to control the boost phase of flight.

Airplane attitude and overall performance were controlled by the pilot within the accuracy of the displays provided. Even though the engine failed to light on the first attempt on two flights and some of the displays failed on several other flights, the pilot was able to successfully complete the flight plans. As a result of physiological factors or extreme motivation, however, on a few missions the pilots made corrections they felt were necessary but which resulted in deviations from the flight plan. The boost acceleration had no effect on the piloting control task, although two of the pilots had difficulty shutting down the engine because of the X-15 throttle location.

INTRODUCTION

Several studies, references 1 to 3, for example, have considered the pilot as the primary controller of the launch of miltistage orbital vehicles. These investigations used simulators which varied in sophistication from relatively simple fixed-base types to motion simulators capable of duplicating the high acceleration that is characteristic of launch vehicles. In these studies it was generally concluded that the use of the pilot to control the launch holds promise. Additional study was recommended, however, to more completely define the optimum use of the pilot during boost.

Although airplanes have been flown to relatively high altitudes (approximately 100,000 ft) and to low dynamic pressures (approximately 5 lb/sq ft), the X-15 is the first airplane designed to be controlled by the pilot at high altitudes in ballistic flight. In an X-15 flight, the pilot must accurately control the flight path during the aerodynamic part of the boost climbout in order to control the apogee of the mission. The performance capability of the X-15 and the operational techniques used during each flight duplicate, to some extent, the initial stage of a multistage launch. The climbout of flights to high altitude, in particular, closely simulates the initial stage of the launch of multistage vehicles. In figure 1 the boost of the X-15 and the first stage of a Saturn C-5 launch are compared at similar altitudes and velocities. It is apparent that the launch dynamic pressures and longitudinal-acceleration environments of the vehicles are similar, although the pitch-angle programs to achieve the desired flight path differ markedly. This dissimilarity is to be expected, inasmuch as the comparison is between a vertical and a horizontal launch.

This paper presents data from X-15 flights that are similar to the launch of boost vehicles in an attempt to better define the optimum use of the pilot during boost. Considered is the performance of the pilot in the powered, or boosted, portions of envelope-expansion flights made during the joint NASA-Air Force-Navy X-15 program at Edwards, Calif. Two airplane configurations and three different types of controls were used during the tests. The maximum altitudes attained covered the range from 154,000 feet to 354,200 feet.

SYMBOLS

a_x	longitudinal acceleration, g
a_z	normal acceleration, g
g	acceleration due to gravity, ft/sec^2
h	altitude, ft
$h_{(a_x=0)}$	altitude at zero longitudinal acceleration, ft
q	dynamic pressure, lb/sq ft
t	time, sec
$t_{(a_x=0)}$	time from engine light to zero longitudinal acceleration, sec
t_b	time from engine light to thrust reduction, sec
V	velocity, ft/sec
α	angle of attack, deg
δ_h	horizontal-stabilizer position, deg
ζ	damping ratio
θ	pitch angle, deg
φ	bank angle, deg
ψ	heading angle, deg
ω_n	undamped natural frequency, radians/sec

Subscript:

max maximum

AIRPLANE AND SYSTEMS

Airplane

The X-15 is a single-place, rocket-powered airplane (fig. 2) designed for flight at hypersonic speeds and extreme altitudes. The airplane is carried aloft under the right wing of a B-52 and is launched at an altitude of about 45,000 feet and a Mach number of about 0.80. After launch, the X-15 performs a powered flight mission, followed by a deceleration glide prior to vectoring for a landing. With this operational technique, the airplane is capable of attaining a Mach number of 6 and can be flown to and recovered from an altitude in excess of 300,000 feet.

Flights to high altitudes have been made with all three of the X-15 airplanes in two configurations: the basic and the ventral off. The configuration shown in figure 2 is referred to as the basic configuration. For the ventral-off configuration the lower movable vertical surface (dashed line) was removed, as discussed subsequently.

Aerodynamic control is provided through conventional aerodynamic surfaces, with vertical surfaces used for yaw control and the horizontal tail for both pitch and roll control. All of the aerodynamic control surfaces are actuated by irreversible hydraulic systems. Control force is provided by bungee for pilot feel. A conventional center stick is used for pitch and roll control, and rudder pedals are used for yaw control; however, a side-located stick is provided for control of pitch and roll in high-acceleration environments at the option of the pilot. Most of the X-15 missions have been made with the side stick, although the pilots used the center stick on their first flights.

Figure 3 is a photograph of the X-15 cockpit showing the two aerodynamic control sticks (center and right) and the rudder pedals. Also shown is the pilot's display. The primary flight control displays are on the upper part of the panel above the white line.

A closeup of the attitude display is shown in figure 4. Angle of attack is of primary importance in establishing the climb attitude and can be read to within 1°. Thus, with good aerodynamic characteristics, the pilot would be expected to control to this accuracy. For some flights, however, normal acceleration was used as the prime pullup control quantity.

Shown also in figure 4 is the three-axis attitude indicator which displays angles of attack and sideslip, bank angle, heading, and pitch attitude. To the left of the indicator is the pitch-attitude vernier which, with the null pointer, gives attitude in degrees. Once the flight plan is formulated, the vernier null is set to the desired pitch angle and provides a display of pitch attitude which can be read to within 1°. A nulling vernier for angle of attack, the horizontal bar of the three-axis ball, is also provided and can be preset on the ground for the desired angle of attack. The pitch-angle vernier is important for control of boost, and the angle of attack is used primarily during reentry.

Systems

Display and guidance.- An inertial display and guidance system is incorporated into the airplane to provide the pilot with airplane attitudes about all three axes and with inertial velocity, altitude, and rate of climb. Although the system has provided adequate attitude information, the accuracy and reliability of the inertial velocity and altitude values were not completely acceptable for early flights in the program and, so, were not relied on as primary displays. However, with engineering modifications, flight experience, and the development of procedures and techniques for proper alinement and erection, the system operated within specifications for later flights to high altitude. These specifications were based on 1956 state of the art and do not satisfy the requirements for boost missions.

To provide angle-of-attack and angle-of-sideslip information for the pilot and to make it possible to record these data, a hypersonic flow-direction sensor, referred to as the ball nose, was developed and installed in the X-15 airplanes. The sensor is a null-seeking, hydraulically actuated, electronically controlled servomechanism. Differential pressure is measured, and a signal is fed to hydraulic actuators which position the ball to balance the differential pressure. Flight-test experience and ground checkout show the system to be accurate to ±0.25° at dynamic pressures greater than 10 lb/sq ft.

The accuracy of the inertial data and the usability of the data displayed to the pilot are shown in the following table:

Inertial system design specifications after 300 seconds of operation		Pilot's display	
Quantity	Accuracy	Quantity	Reading per division of displayed quantity[b]
Pitch attitude	0.5°	Pitch attitude	10° (vernier 1°)
Roll attitude	0.5°	Roll attitude	10°
Heading	0.5°	Heading	5°
Total velocity	±100 ft/sec	Total velocity	200 ft/sec
Altitude	±5,000 ft[a]	Altitude	2,000 ft
		Angle of attack	1°
		Angle of sideslip	1°
		Burning time	1 sec

[a]Varies with time; expected error at engine shutdown ±1,500 feet.
[b]Pilot can read between divisions for more accurate estimate.

Augmentation.- To provide adequate handling qualities over the operating envelope of the X-15 airplane, damping augmentation about all three axes is necessary. Flights to high altitudes have been made with two systems that provide augmentation--the stability augmentation system (SAS) and the adaptive control system.

The stability augmentation system (ref. 4) provides auxiliary aerodynamic damping by actuating the aerodynamic control surfaces to oppose the rotational velocity (fig. 5) of the airplane. An interconnect damper system (termed yar) provides a crossfeed yaw-rate signal into the roll-control surfaces. The damper control-surface authority is equal to that of the pilot in pitch and yaw and is twice that of the pilot in roll. Although damper gains may be set by the pilot, gains of 0.6 deg/deg/sec in pitch, 0.3 deg/deg/sec in roll, 0.24 deg/deg/sec in yaw, and 0.54 deg/deg/sec in yar were used during the flights considered.

The adaptive flight control system (ref. 5) has been installed in the X-15-3 airplane. The system is a high-gain rate-command model-control system in pitch and roll and is a high-gain damper system in yaw (fig. 6). A yar interconnect similar to that previously described is also provided. The gain of the system is variable in an attempt to provide constant response (that of the model) throughout the flight envelope. The models in pitch and roll are simple first-order-lag transfer functions with time constants of 0.5 second and 0.3 second, respectively. A damper system is provided in yaw and yar with variable gain. The system utilizes both aerodynamic controls for high-dynamic-pressure conditions and reaction controls for low-dynamic-pressure conditions to provide control over the entire flight regime. At low dynamic pressures, the adaptive-system gains reach peak values and the reaction controls are activated. The reaction controls were activated for the portions of the boost considered herein; however, these controls were used only near the end of boost and did not contribute significantly to flight-path control. Outer control-system loops also provide the capability of holding angle of attack, pitch angle, and bank angle and heading. The hold modes relieve the pilot of the necessity of constantly controlling the flight variable; however, he can, through the adaptive control system, override the hold modes.

Flight tests of the unaugmented X-15 airplane revealed an area in the reentry flight envelope that was uncontrollable when the pilot used conventional control techniques (ref. 6). To improve the lateral controllability of the airplane without augmentation at high angle of attack, the lower movable ventral was removed (fig. 2). This configuration change made the yar interconnects of the stability augmentation and adaptive systems unnecessary and undesirable.

Reaction control.- Although less effective than the aerodynamic controls during the part of the flight to high altitude considered herein, a reaction control system is provided for control of airplane attitude in regions of low dynamic pressure and is activated for a portion of the boost. The basic reaction control system is a proportional acceleration command system capable of about 5.6 deg/sec^2 in roll and 2.0 deg/sec^2 in pitch and yaw for each of two systems.

FLIGHT PROGRAM

Instrumentation

The X-15 airplanes are instrumented to measure and record data for many types of investigations, such as handling qualities, aerodynamic heating, aerodynamic loads, performance, and local flows. In addition, continuous radar-tracking records the flight-path velocity and altitude. The recording instrumentation is accurate to within 2 percent of full scale of the recorded variable; however, for this investigation, the recorded quantities are used more qualitatively than quantitatively.

Flight Tests

The flight tests reported herein were part of an overall flight program designed to expand the X-15 flight envelope into high-altitude regions not previously traversed by winged vehicles. The altitude-buildup sequence was similar to that used in other research airplane programs. Flight plans were formulated by using the six-degree-of-freedom X-15 simulator (ref. 7). A typical flight plan is shown in table I. The plans were practiced by the pilot on the simulator until he was thoroughly familiar with all aspects of the flight. He then performed the mission according to the flight plan by using the cockpit displays and with the assistance of a ground controller who monitored the progress of the flight and suggested corrections to the flight path by radio call. Airplane and system performance were also monitored on the ground during the flights. Pertinent information on the airplane configuration, control system, burnout altitude and velocity, and maximum dynamic pressure during boost are presented in table II for the flights considered. Also included, to be discussed later, is the pilot rating of the boost control task.

Piloting Task

Since the exit attitude of the X-15 is established at relatively high dynamic pressure, the aerodynamic stability, control, and damping of the airplane are important. These airplane characteristics are considered to be satisfactory by the pilots with the augmentation systems operating (ref. 8). The exit control task is primarily that of establishing and controlling pitch attitude to the desired value while controlling bank angle to zero and heading to the angle specified.

The longitudinal static stability and damping of the basic airplane during a typical boost to an altitude of 250,000 feet are shown in figures 7 and 8, respectively. The airplane is statically stable (fig. 7) through burnout (approximately $t = 90$ sec). From figure 8, it is apparent that the inherent aerodynamic damping is low; damping ratio is less than one-tenth during most of the boost. With damping augmentation, however, the ratio is above 0.3 through most of the boost.

The airplane response characteristics with the adaptive control system are represented by the system models at normal aerodynamic flight conditions such as the establishment of the boost attitude; however, with the large decrease in dynamic pressure near burnout, low aerodynamic-control effectiveness deteriorates the capability of the system to force the airplane to the response of the model.

The typical flight plan shown in table I is for the design altitude mission to 250,000 feet. This mission required a pullup to an angle of attack of 10° or 2.5g until a pitch angle of 37° was reached. Pitch attitude was then held constant to burnout.

Some of the flights considered in this study were planned to allow engine thrusting to fuel exhaustion, whereas others requested the pilot to shut down the engine after a specified burning time or at a specified velocity. Burning time was selected as the primary quantity with which to control final velocity when the inertial-velocity data proved to be less accurate than desired. During later flights to high altitude, however, the pilots have relied on inertial velocity as the prime cue for engine shutdown.

Flights to high altitude were made with three types of controls. With the stability augmentation system and the adaptive control system, the pilot controls pitch, roll, and yaw continuously. With the adaptive system, however, he controls through a rate command control system in pitch and roll to achieve the desired attitude. Also, with the adaptive system, hold modes are provided which, at the pilot's selection, automatically hold pitch attitude, angle of attack, or bank angle. Near zero bank angle, the system also holds heading.

RESULTS AND DISCUSSION

Representative Boosts

Data from representative X-15 boosts to high altitude with the stability-augmentation-system controls and the adaptive-system controls are presented in figures 9 and 10, respectively. In addition to the performance quantities of altitude, velocity, and dynamic pressure, normal and longitudinal acceleration, bank angle, heading angle, angle of attack, pitch angle, and longitudinal control position are presented. The planned pitch angle, normal acceleration, thrusting time, and burnout or shutdown conditions are included for comparison with the flight data. Additional time histories of flights performed to expand the altitude of the airplane are presented and discussed in the appendix. Pertinent information concerning each flight is summarized in table II.

Figure 9 presents a boost of the X-15 airplane to an altitude of 226,400 feet with the stability augmentation system. The flight plan called for a 2g pullup to a pitch angle of 33°. This pitch angle was to be held until engine shutdown, and a constant bank angle of zero and a heading of 214° were requested. The pilot attained less than 2g during rotation, but the pitch angle was held to within the limits of the accuracy of the displayed quantities. Deterioration in aerodynamic damping is evident near the time of engine shutdown.

Using the inertial velocity as a cue, the pilot shut down the engine at 5,280 ft/sec rather than the requested 5,200 ft/sec. The maximum altitude attained was 6,400 feet above the planned altitude of 220,000 feet. From launch to engine shutdown, bank angle was held to within 10° of zero and heading was held to within 3° of the desired value of 214°.

The following comments are excerpted from the questionnaire completed by the pilot following the flight of figure 9:

> The piloting technique used to arrive at the planned engine shutdown conditions was to fly pitch attitude, hold heading, and observe the relationship between altitude, velocity, and burning time. My final checkpoint to decide whether the flight was high or low was 92,000 feet at 60 seconds. At this point, it was right on. Watching velocity for shutdown, it appeared to come around 134,000 feet rather than the planned altitude of 131,000 feet. The heading flown was 214°. The throttle setting was reduced at 5,200 ft/sec when the elapsed burning time reached 81 seconds. There was a noticeable delay between throttle cutoff and actual engine shutoff, although there was a thrust reduction with reduction of throttle. Engine shutdown was programed on inertial velocity.
>
> At the higher dynamic pressures (initial portion of the climb), the control was really not too bad. The only problem was extraneous pilot inputs and necessary corrections for heading. However, after about 50 seconds of burning, the pitch task was more difficult because of an inability to trim pitch to take care of the attitude droop at about 100,000 feet. An almost constant-amplitude pitch cycle of ±2° was induced near burnout. No attempt was made to stop the oscillation at exactly 33°.

The pilot rated the boost control task at 1.5 in pitch, 1.2 in roll, and 1.2 in heading, based on the Cooper scale (ref. 9).

Data from a boost to an altitude of 285,000 feet using the adaptive control system with both pitch-angle and bank- and heading-angle hold are presented in figure 10. For this flight a 2g rotation was also specified, however, to a pitch angle of 42°. Engine shutdown at 5,100 ft/sec was requested and the pilot, using a presentation of inertial velocity, achieved a maximum velocity of 5,160 ft/sec. The pilot indicated that he had difficulty setting up the hold mode and, so, overrode the pitch-attitude hold to control the pitch angle to within the accuracy expected. Bank-angle and heading excursions with the system hold modes in operation were somewhat lower than they would have been with normal control. The pilot made the following comments concerning the hold modes:

> The pitch-angle vernier seemed to be right on, but the three-axis ball was 4° or 5° low. A pitch angle of 42° was established, and pitch hold was engaged. Something was out of trim, so the stick was retrimmed. I only had one chance

to look at it because I had to move my head. As far as I could tell, I was within 1/2° of zero on the stick, and it still wouldn't do it. So, I decided to discount the fact that pitch hold was on and fly manually, overriding the pitch hold.

The ground guidance callouts were right on all the way and came nearly as quickly as the errors were observed. It was concluded from the first good check on time versus velocity that the flight profile was low. At the next 10-second check, I was still a little low. At 70 seconds, the flight was on profile.

It was a little difficult to hold a 42° pitch angle with the mismatch between the pitch attitude shown on the ball and the pitch attitude the system was trying to hold. It wasn't difficult to control, but it was a constant effort.

The pilot also said he sensed an apparent change in pitch attitude by the reduction in external light entering the cockpit. The combined control task was rated as 3 in pitch, 1.5 in roll, and 1.5 in heading.

Presentation of Results

The results obtained during the expansion of the flight envelope of the X-15 are summarized in figures 11 to 16. The planned and the actual prime control quantities are compared for the boost missions. The data are from flights in which the pilot used either the conventional control system with horizontal-stabilizer trim and stability augmentation or the adaptive control system.

Pitch attitude.- As previously indicated, the accuracy of the displayed pitch angle was ±0.5° and could be read by the pilot to within ±0.5°. Thus, the maximum accuracy to be expected of the pilot in controlling this piloting task is ±0.7°. How well the pilot flew the boost mission, considering the accuracy of the displayed quantities, is shown in figure 11 in which the planned and the average pitch angles are compared. The pilots controlled to within the display limits in about two-thirds of the boosts to high altitude. The data show poorer overall performance using the adaptive system with the hold modes than with the manual systems. In some instances, the pilot controlled to higher than desired pitch angles; in other instances, to be discussed later, he undershot the desired pitch angle. The data do show that the pilot can control this boost task to within the accuracy of the displayed quantities, whether controlling manually or with the hold modes.

Velocity.- Another task of primary importance for the control of boost is the control of velocity at engine shutdown. Figure 12 compares the actual and the planned velocities. The flagged symbols indicate the boosts in which inertial-velocity data were used as the primary cue for engine shutdown. For these boosts the average deviation from the desired maximum velocity was 50 ft/sec, which is well within the accuracy of the displayed data. When burning time was used as the primary cue for engine shutdown, the average final velocity deviated approximately 200 ft/sec from the desired value. These large variations were expected and accepted, inasmuch as engine thrust has varied from 57,000 pounds to 60,000 pounds from flight to flight and engine to engine. When feasible, the thrust of the rocket engine was measured and the simulation altered to reflect the correct thrust so that a more realistic prediction of performance could be made during flight planning.

Engine burning time.- Figure 13 compares the time of throttle retardation and of actual zero longitudinal acceleration to the desired burning time as predicted on the fixed-base piloted simulator. These data and the data of the previous figure show that, although the pilot often succeeded in attaining the desired velocity, he never accomplished the task in the time predicted during flight rehearsal on the simulator. Attempts were made to provide the simulator with actual engine thrust characteristics, but these data were not always available and, thus, predicted performance may not have been exact. The pilots indicated that they retarded throttle on the velocity or time cue without regard for the tail-off characteristics of the rocket engine. The actual time of throttle retardation (fig. 13(a)) and the desired engine shutdown time are in much better agreement than the actual time of zero longitudinal acceleration (fig. 13(b)) and the desired time. It appears that the pilots were motivated to allow at least the planned burning time in an attempt to attain at least the desired velocity. In every case, the pilots either shut down the engine at the scheduled burning time or allowed it to burn longer than planned. In two instances, they had difficulty in reaching the throttle, under the 3.5g longitudinal acceleration, to cut off the engine. This difficulty has been alleviated by moving the throttle to a more convenient location.

Heading and altitude.- In addition to the foregoing control tasks, the pilot controlled airplane heading and, less directly, altitude. Figure 14 presents data on the pilot's performance in controlling to the desired heading. In addition to the cockpit display, the pilot was advised during the flight of his ground-track heading by a ground controller. Inasmuch as the airplane heading can be estimated only within 2° to 3° with the pilot's display, the accuracy in holding heading shown in the figure is acceptable for the X-15 mission. Little difference is apparent between the pilots' performances when controlling manually or when using the heading hold mode.

Although the control of altitude was not of primary importance, altitude was one of the quantities checked as the pilot mentally computed a "how goes it" curve during the mission. Figure 15 compares the actual and the predicted altitude at engine shutdown. The average deviation from the desired altitude was about 7,000 feet. An extreme of about 20,000 feet occurred during a flight when the pilot was highly motivated to better or at least achieve the desired maximum altitude. The flight point (actual $h_{(a_X=0)} \approx 90{,}000$ ft) significantly lower than the desired value occurred on a pilot's first flight to high altitude. He did not believe the instrument readings and pushed over to check attitude. When he pulled up a second time, insufficient burning remained to attain the desired altitude.

Piloting performance in controlling altitude was essentially the same with each of the control systems used.

Maximum altitude.- The altitude-buildup program was designed to safely demonstrate the altitude capability of the X-15 airplane. The piloting technique of pulling up to a given pitch attitude during engine thrusting and holding a constant pitch attitude for a specified thrusting time with known engine performance resulted in reasonable control of maximum altitude for the X-15 mission. Figure 16 compares the actual and the planned maximum altitudes. The mean difference was about 14,000 feet, with an extreme excursion of 35,000 feet from the planned altitude. However, considering only the displayed parameters of burnout velocity and pitch angle, which for the X-15 are the prime controllers of maximum altitude, the expected error in final altitude from these sources for a 250,000-foot flight would be approximately 13,000 feet. It appears that the pilots were motivated to achieve at least the desired maximum altitude; in most instances the desired altitude was exceeded, but the mean deviation was not more than would be expected from the quantities displayed.

With displays of inertial velocity and pitch attitude, the pilots controlled to within 2 percent of the desired altitude. This performance was about four times as accurate as could be expected, considering the accuracy of presented data and of display interpretation. Although these accuracies are poor compared to orbital insertion and rendezvous requirements, the X-15 mission has no need for greater accuracies. It does appear, however, that the control precision obtainable with the X-15 may be adequate for controlling the first stage of multistage vehicles.

Pilot Ratings and Performance

Each phase of an X-15 flight is evaluated by the pilot, using an adaptation of the Cooper rating scale (ref. 9). The ratings obtained for the pitch, roll, and yaw modes of the boost control are summarized in table II. The controllability in pitch was sometimes rated slightly lower than the other control modes, perhaps because pitch was the mode of primary control. Average ratings for the stability augmentation system and the rate command and hold modes of the adaptive system were similar.

The X-15 boost stability and damping in pitch and characteristics rated as satisfactory during two other investigations (refs. 10 and 11) are compared in figure 17. Reference 10 includes pilot evaluation under relatively high acceleration environments during centrifuge tests, and reference 11 presents results from a flight evaluation using a variable-stability airplane. Much of the X-15 boost controllability in these studies was predicted to be satisfactory. The average rating by the X-15 pilots was 1.9, well in the satisfactory range. However, the control task was rated one to two numbers lower after about 75 seconds of boost in regions of low dynamic pressure where aerodynamic forces were low. The pilots demonstrated that they could easily control to the desired values. They felt that they could control to $\pm 0.15g$ in pullups, $\pm 10^\circ$ in bank angle, and $\pm 1^\circ$ in angle of attack and angle of pitch.

Although the pilots stated that the 3.5g longitudinal acceleration did not lessen their ability to perform the control task, in two instances they had difficulty shutting down the engine. After a slight relocation of the throttle, no difficulty was encountered in performing the required tasks under the acceleration environment. For the accelerations encountered in this boost the pilots did not feel that a centrifuge program would be required for training purposes. They indicated, however, that the centrifuge tests in which they participated did give them confidence in their ability to perform effectively under typical boost-acceleration environments.

On the first flight to high altitude for each of two pilots, a sensation of continued rotation (pitching up) during climb under high thrust was reported. One of the pilots pushed over to check the horizon, and the other requested a check of the attitude by the ground controller to verify his instrument readings. There was at least one flight during which the pilot was so highly motivated that he flew to a higher altitude than planned.

On at least two occasions the engine failed to start on the first attempt, but the pilot was able to light it on the second try and to satisfactorily follow the flight plan. For several flights some part of the displays failed, but, by using other displayed quantities, the pilot completed the flight. On many flights the pilot's evaluation of the progress of the flight and his resultant corrections contributed significantly, as evidenced by the number of flights in which the desired burnout conditions were achieved by burning longer than planned.

Although none of the pilots reported any engine light or burnout transients, low-magnitude transients were noted on some of the flights. It has not been possible, however, to isolate engine-caused transients from pilot control disturbances.

During the initial system evaluation, the pilots were reluctant to delegate complete control to hold modes of the adaptive system. In some of the flights with the hold modes operative, the records show that the pilots overrode the selected hold mode. A more thorough analysis than is feasible for this study would be required to determine if the pilot improved or degraded the hold operation. In general, the pilots commented favorably on the hold modes, especially bank and heading, and, with experience, used them with more confidence.

CONCLUDING REMARKS

Pilot control of the boost phase of the X-15 airplane to high altitude--a boost that is similar to the first stage of the boost of vertically launched multistaged vehicles--has been demonstrated to acceptable accuracy on many flights. In most instances, the pilots controlled to within the accuracy of the displayed information and, in other instances, were able to complete the flight even though the engine failed to light on the first attempt and some of the displays malfunctioned. On a few flights, however, as a result of physiological factors or extreme motivation, the pilots made corrections they felt were necessary but which resulted in deviations from the flight plan. The boost acceleration had no effect on the control task.

With correct vehicle design for the inclusion of the pilot in the control loop and with proper pilot training, it is believed that the pilot can effectively control the boost of launch vehicles.

Flight Research Center,
National Aeronautics and Space Administration,
Edwards, Calif., February 18, 1964.

APPENDIX

X-15 BOOSTS

Data from the boost portions of 16 X-15 flights to high altitude, showing the actual performance of the pilot compared to the specified flight plan, are presented in figures 18(a) to 18(p). As indicated in table II, the data are from boosts performed by four pilots, denoted as A, B, C, and D, to maximum altitudes from 154,000 feet to 354,200 feet.

Presented in figure 18(a) are data from a mission to evaluate the backup stability augmentation system. Pilot performance and final boost velocity are of interest. The flight plan called for an angle-of-attack pullup of 10° until a pitch angle of 30° was achieved, a pitch-over to zero g after 35 seconds of thrust time, and a pullup to 1.5g after 75 seconds of thrust time. Fuel exhaustion occurred within 1 second of the planned time and within 230 ft/sec of the desired velocity. Considering the maneuvering required during the flight, the actual and desired data compare reasonably well.

Figure 18(b) illustrates a flight designed to investigate the stability and control of the ventral-off configuration and the limit-cycle characteristics of the adaptive control system. This flight plan specified a pullup to an angle of attack of 6° until a pitch angle of 20° was reached, and then a push-over to an angle of attack of 2°. Engine shutdown was required after 80 seconds of burning at a velocity of 5,600 ft/sec and at a longitudinal acceleration of 3.2g. The pilot successfully followed the specified flight plan.

Figure 18(c) presents data from a boost that is more typical of a launch control task, which requires controlling to a pitch-attitude schedule, than the flights of figures 18(a) and 18(b). A rotation at 1.5g was planned to a pitch angle of 35°, which was to be held constant until burnout. Although the engine did not start on the first attempt, the pilot was able to light it on the second try. The mission was completed successfully, and a final velocity within 100 ft/sec of the planned value was obtained by burning 2 seconds longer than planned.

The third evaluation flight of the adaptive control system is shown in figure 18(d), which presents a boost at 100-percent thrust to a maximum altitude of about 180,000 feet. A low-angle-of-attack pullup (6°) was planned to evaluate the effect of high dynamic pressure on the adaptive system. A delayed engine light resulted in a lower altitude trajectory than planned, but the objectives of the flight were accomplished. Shutdown of the engine was achieved on velocity cue, since the engine light was delayed some 25 seconds. By using the pitch-angle hold mode of the adaptive system, pitch angle was maintained within ±1° and, with increased burning time, the pilot was able to shut down the engine near the desired velocity.

A boost similar to that of figure 18(d) is presented in figure 18(e). The flight plan called for a pullup at an angle of attack of 7° until a pitch angle of 32° was reached. This angle was to be held until burnout. The pilot controlled to within 1° of the desired pitch attitude to about $t = 60$ seconds, when he became slightly disoriented. Although his display indicated the correct pitch angle of 32°, he felt that the airplane was continuing to rotate. He pushed down to check the horizon and then pulled up to the desired pitch angle. This deviation from the flight plan resulted in a lower-than-planned final altitude. Additional burning time was allowed by the pilot with a slow retardation of the throttle, and engine shutdown was accomplished at a velocity near the desired value.

Figure 18(f) presents data from a flight on which an altitude of 193,600 feet was attained. The flight plan requested a pullup at an angle of attack of 10° until a pitch angle of 32° was reached. This pitch angle was to be held constant. After 70 seconds of boost, the pilot was requested to push over to zero g. For the most part, the flight plan was followed to within acceptable limits, with the pilot manually flying the entire mission. Fuel exhaustion occurred within 1 second of the desired time, but the desired burnout velocity was not achieved.

The fourth flight with the adaptive control system (fig. 18(g)) was designed to investigate the hold modes. A maximum altitude of 207,500 feet was attained. The flight plan required a pullup at an angle of attack of 10° to a pitch angle of 30°. After 35 seconds of thrusting, a push-over to zero g was requested, and after 55 seconds a pullup to 1.4g was planned until a pitch angle of 32° was reached. The roll hold mode was engaged just after launch and remained in operation throughout the boost. The engine was shut down late, which resulted in a velocity at burnout 200 ft/sec higher than planned. As a result of the maneuvering required, pitch angle was not completely stabilized at burnout, and average values were about 2° lower than planned. The maximum altitude was 2,500 feet higher than planned, the higher velocity compensating for the lower pitch angle.

The flight represented in figure 18(h) was planned for a maximum altitude of 206,000 feet. The roll hold mode was used, but the pitch program was flown manually through the adaptive rate command control system. Although the pitch attitude held was slightly less than planned, the burnout velocity, which was controlled by using the inertial velocity as the primary engine shutdown cue, was within 50 ft/sec of the desired value. The maximum altitude, however, was about 3,000 feet higher than planned. This correlation is well within the accuracy expected of the X-15 systems.

The flight shown in figure 18(i) was an altitude-buildup flight with the stability augmentation control system. The flight plan required a pullup at an angle of attack of 10° until a pitch angle of 32° was attained. Pitch angle was to be held constant until engine shutdown at $t = 79$ seconds and a velocity of 5,000 ft/sec. Accurate control of angle of attack and angle of pitch was achieved by the pilot, although 2° lower than planned. The engine was shut down 2 seconds later than specified, which resulted in a shutdown velocity 360 ft/sec higher than planned. For this flight, the prime engine shutdown cue, elapsed burning time, was unavailable since the cockpit clock failed after launch.

Figure 18(j) presents the first altitude flight for pilot D. A climb at a pitch angle of 33° was planned, with engine shutdown at a velocity of 5,200 ft/sec resulting in an altitude of 220,000 feet. The altimeter did not operate, so ground callout was used for altitude information. Actual maximum velocity was 5,240 ft/sec, again using inertial velocity as the primary cue for engine shutdown. The pitch angle held by the pilot was about 1° higher than planned, but the pilot indicated that he was late in establishing the correct pitch attitude. This would have resulted in a lower maximum altitude, but the pilot compensated by flying a slightly higher pitch angle which resulted in a maximum altitude of 223,700 feet.

Figures 18(k) to 18(l) present flights to the design altitude of the airplane with the adaptive and the stability augmentation systems, respectively. The flight plans were similar, requiring a pullup to a pitch angle of 37° with the adaptive system and a pitch angle of 38° with the stability augmentation system. These angles were to be held until engine shutdown. For both flights, the longitudinal acceleration was about 3.5g at engine shutdown. Piloting performance in holding the desired pitch attitude was similar in each flight. Neither pilot achieved the desired engine shutdown velocity. The maximum velocity in each flight was about 130 ft/sec under the desired velocity. Pilot B shut down the engine at the desired time. He used the bank-angle and pitch-angle hold modes of the adaptive system, which simplified the control task.

Figure 18(m) shows the boost to an altitude of about 272,000 feet with the adaptive control system. The hold modes were not engaged for this flight. A pullup to 2g was to be used to attain a pitch angle of 38°, which was to be held until engine shutdown. Although the flight plan requested a 2g pullup, a stabilized acceleration level of 2g was never achieved. Under the 3.5g acceleration at engine shutdown, the pilot indicated that he had difficulty reaching the throttle to shut down the engine. Shutdown was about 3 seconds late, and final velocity was more than 400 ft/sec higher than planned.

The boost phase of a flight to an altitude of 314,750 feet is presented in figure 18(n). The flight was accomplished by pilot B with the adaptive control system. Both bank-angle and pitch-angle hold modes were used. A pitch angle slightly higher than planned was held throughout the thrusting time, which resulted in a somewhat higher altitude than planned. Burnout was planned at a velocity of 5,150 ft/sec after 80 seconds of thrusting, but occurred about 2 seconds late and at a higher velocity than planned. The rocket engine achieved more than normal thrust and burning time.

Figure 18(o) presents a boost to an altitude of about 348,000 feet. The flight plan specified a climb using a pitch angle of 44° to a maximum altitude of 315,000 feet. Shutdown of the engine was specified at a velocity of 5,400 ft/sec; actual maximum velocity was 5,380 ft/sec using inertial velocity as a cue. The overshoot in altitude, it appears, resulted from holding the pitch angle 1° to 2° higher than planned. The pilot reported that, early in the flight, the ground controller indicated that the flight profile was low, so he pulled up approximately 2° to compensate. The overshoot of 33,000 feet is about two to three times greater than expected from the uncertainty of the displayed quantities.

The flight plan for figure 18(p) called for a climb using a pitch angle of 48° to engine shutdown in order to attain a maximum altitude of 360,000 feet. For this flight, an altitude-predictor instrument was mechanized as a special pilot's display. The instrument presented a conversion of total climb energy into a final altitude prediction. For control, the roll hold was used and the pitch profile was flown manually with the adaptive system. Engine shutdown was accomplished on cue from the altitude predictor at a velocity of 5,520 ft/sec. This flight was the first high-altitude mission on which the predictor was used. The pilot used a crosscheck of actual altitude and the predicted altitude to correct pitch angle. Pitch-angle control was poorer than normal. However, with the increased velocity at engine shutdown, a maximum altitude of 354,200 feet was attained, which is within the accuracy of altitude control expected of the X-15 systems.

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TABLE I.- TYPICAL X-15 FLIGHT PLAN

X-15 FLIGHT REQUEST

Flight No.: 3-6-10 Scheduled Date: June 21, 1962

Pilot: Major Robert White

Subject of Test: Contractual demonstration of MH-96 flight control system

Launch: Delamar Lake on a heading of 205° with MH-96 flight control system (FCS) on adaptive damper, flight control system reaction controls "off," and both ballistic control systems "on."

Item	Time	h, ft	V, ft/sec	α, deg	q, lb/sq ft	Event
1	0	45	790	1.5	145	Launch using side stick, light engine and increase to 100%, rotate using side stick trim (approx. -5) to $\theta = 37°$, $\alpha = 15°$, $g \approx 2.5$. Do not exceed 3g.
2	25	50	1,700	10	440	Engage φ, hold with heading 205° and $\varphi \approx 0°$, and at $\theta = 37°$ trim zero pitch rate and engage θ. Hold, trim $\theta = 37°$.
3	60	100	3,700	6	200	FCS reaction controls "Auto."
4	80	148	5,400	7	60	Shut down engine and engage α hold. Trim $\alpha < 10°$.
5	115	220	5,000	8	4	Disengage hold modes and fly manually (right stick) to maintain heading, $\varphi \approx 0°$ and $\theta \approx 0°$. Ball nose will be unreliable.
6	165	250	4,700			At peak altitude, set $\theta \approx 0°$, engage θ hold and maintain $\theta = 0°$ until $\alpha \approx 20°$ and is reliable ($\delta_h \approx 25°$).
7	210	220	4,900	20	5	When α is reliable, engage α hold and trim $\alpha = 20°$ for entry ($\delta_h \approx 25°$).
8	250	130	5,400	20	120	At 1 g turn FCS reaction controls "off" and maintain $\alpha = 20°$ until 5.5g. If g-limiting has not occurred, decrease α to maintain 5.5g maximum.
9	280	80	4,000	17	650	When level (speed brakes full open), disengage α hold, push over to zero g, and engage φ hold at $\varphi \approx 0°$.
10	300	80	3,500	3	480	Start a space-positioning turn ($\varphi < 60°$), hold turn for 10°, then release the control. Jettison as desired (H_2O_2 off).
11						Disengage hold modes and use control-stick steering for turn to high key.
12						High key. Check ventral armed and pressurize tanks.
13						Low key. Approach speed 300 KIAS, land at 2-mile markers.
14						After touchdown, disengage MH-96 FCS.
15						Before auxiliary-power-unit shutdown, cycle controls, flaps up, trim $\delta_h = 0°$, push-to-test ball nose, and turn data off.

TABLE II.- SUMMARY OF FLIGHT DATA

Figure	Pilot	Airplane configuration	Control configuration	$h(a_x=0)$, ft	V_{max}, ft/sec	t_b, sec	$t(a_x=0)$, sec	q_{max}, lb/sq ft	h_{max}, ft	Pilot rating		
										Pitch	Roll	Yaw
18(a)	A	Basic	SAS	91,000	5,670	84.0	84.7	877	154,000	2	2	2
18(b)	A	Ventral off	Adaptive	95,200	5,630	81.1	82.2	774	160,000	1.5	1.5	1.5
18(c)	A	Basic	SAS	103,000	3,800	81.8	83.7	1,060	170,000	---	---	---
18(d)	C	Basic	Adaptive φ, θ hold	97,500	4,180	79.2	80.0	1,404	180,000	3	3	3
18(e)	B	Basic	Adaptive	117,600	5,158	----	81.6	1,070	184,600	1	1	1
18(f)	A	Basic	Adaptive	134,300	5,520	83.7	86.0	648	193,600	2	1	2
18(g)	C	Basic	Adaptive φ, α hold	119,700	5,557	82.3	83.8	1,082	207,500	3	3	2
18(h)	A	Ventral off	Adaptive φ hold	132,200	4,950	78.9	80.6	716	209,400	1.5	1	1
18(i)	B	Basic	SAS	135,500	5,350	81.1	87.1	708	217,000	2	2	2
18(j)	D	Ventral off	Adaptive	132,000	5,240	79.2	80.5	632	223,700	2.5	2	2
9	A	Ventral off	SAS	145,500	5,280	83.3	85.3	476	226,400	2	1.2	1.2
18(k)	B	Basic	Adaptive φ, θ hold	139,000	5,270	80.0	82.0	783	246,700	2	1	1
18(l)	A	Basic	SAS	143,500	5,117	81.7	83.0	642	247,000	1.5	2.5	1
18(m)	A	Ventral off	Adaptive	148,300	5,660	80.1	83.1	498	271,700	1	1	1
10		Ventral off	Adaptive φ, θ hold	154,000	5,160	79.7	81.9	626	285,000	3	1.5	1.5
18(n)	B	Basic	Adaptive φ, θ hold	160,500	5,510	82.1	84.3	850	314,750	2	1	1
18(o)	A	Ventral off	Adaptive φ hold	171,000	5,380	84.0	86.9	570	347,800	1.2	1	1.5
18(p)	A	Ventral off	Adaptive φ hold	171,000	5,520	85.3	87.9	724	354,200	1.5	1	1

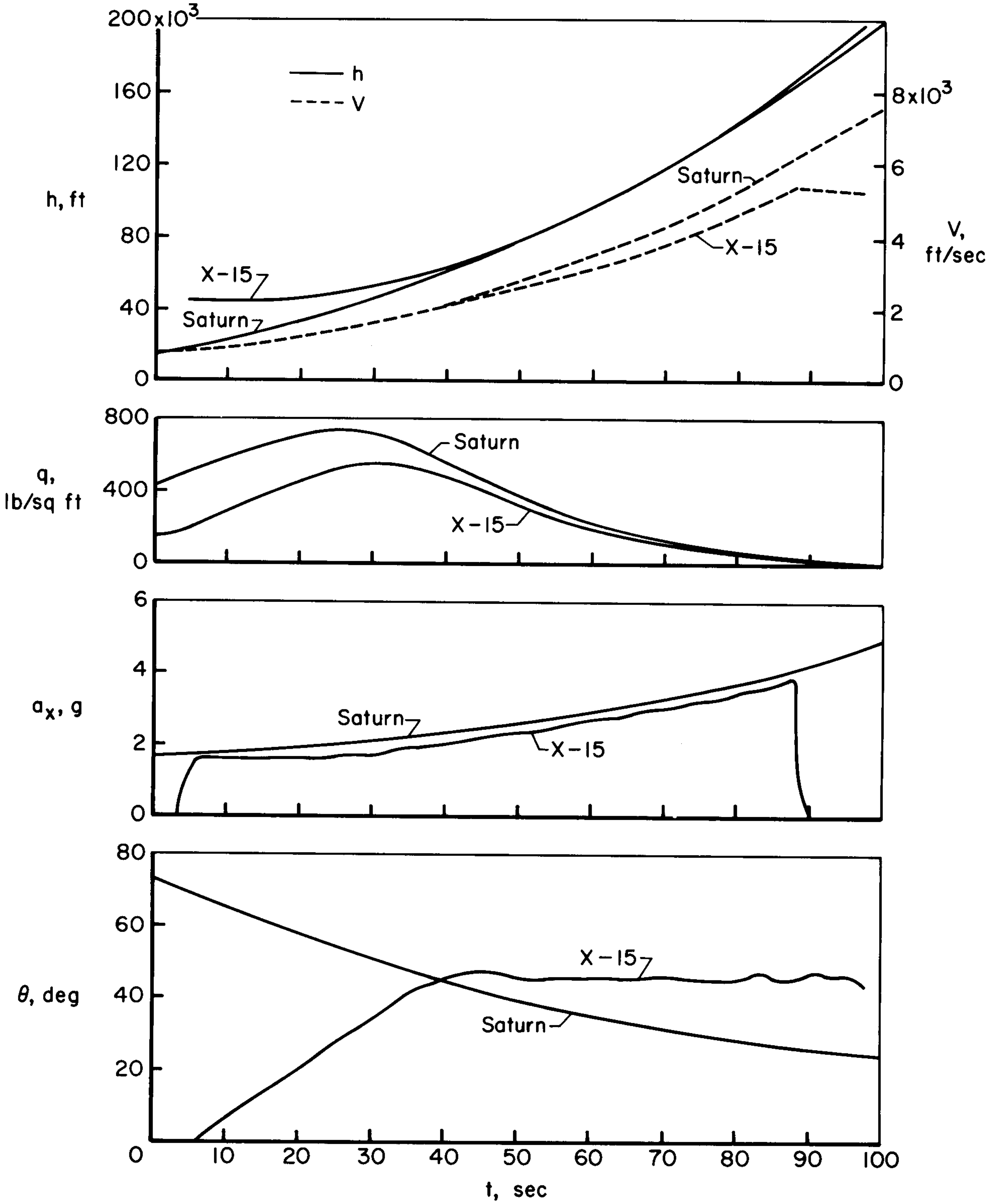


Figure 1.- Comparison of X-15 and typical Saturn C-5 boost.

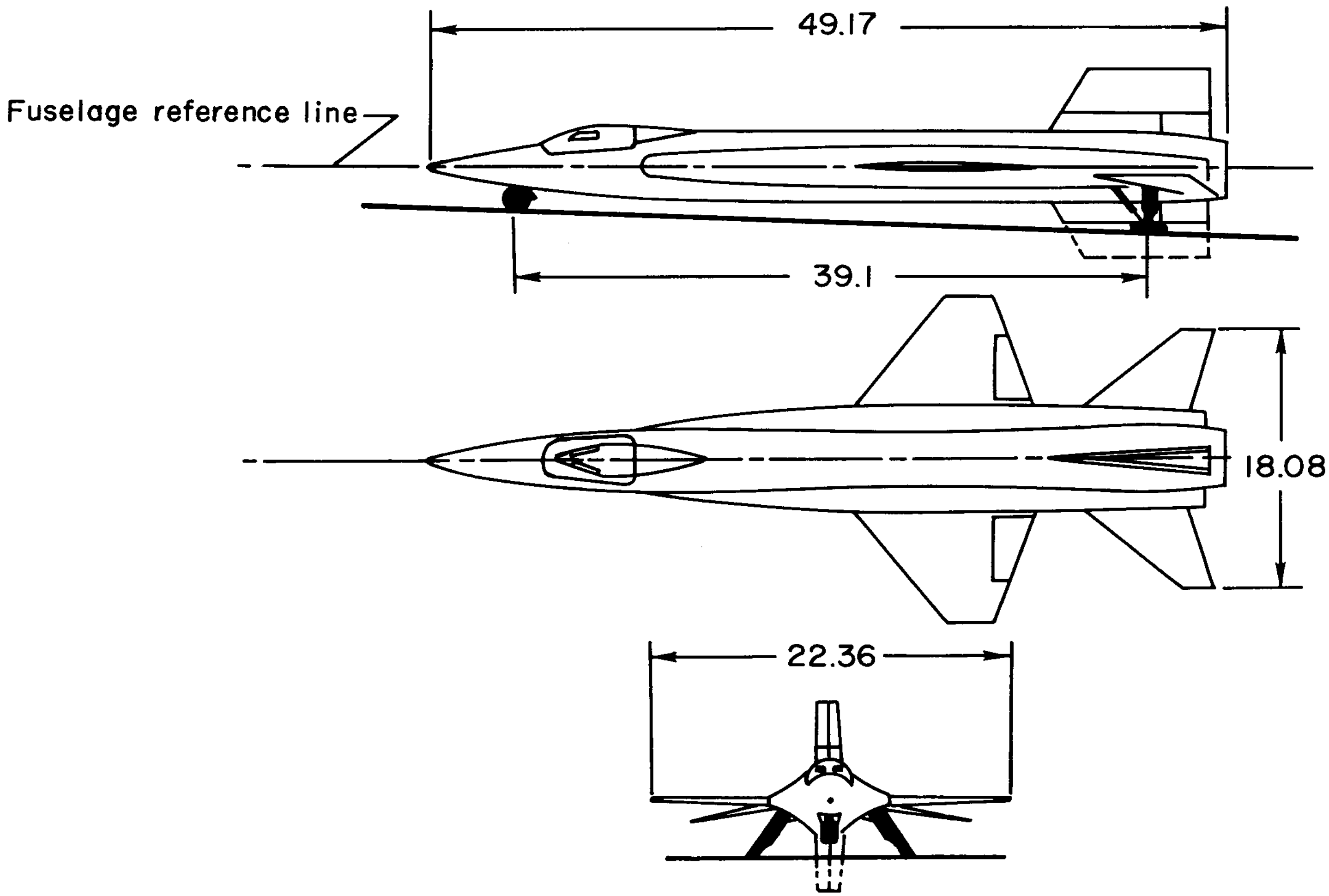


Figure 2.- Three-view drawing of the X-15 airplane. All dimensions in feet.

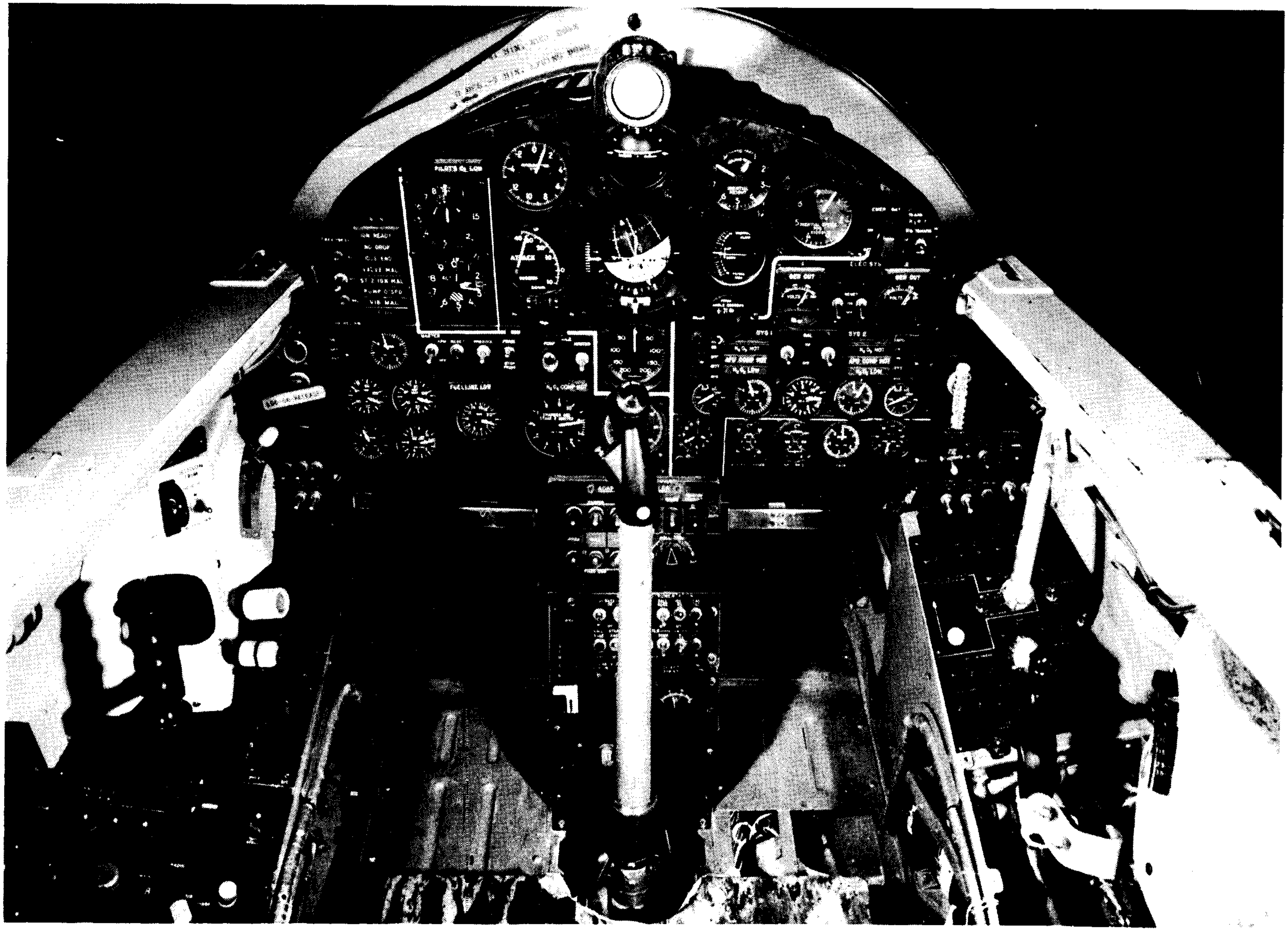
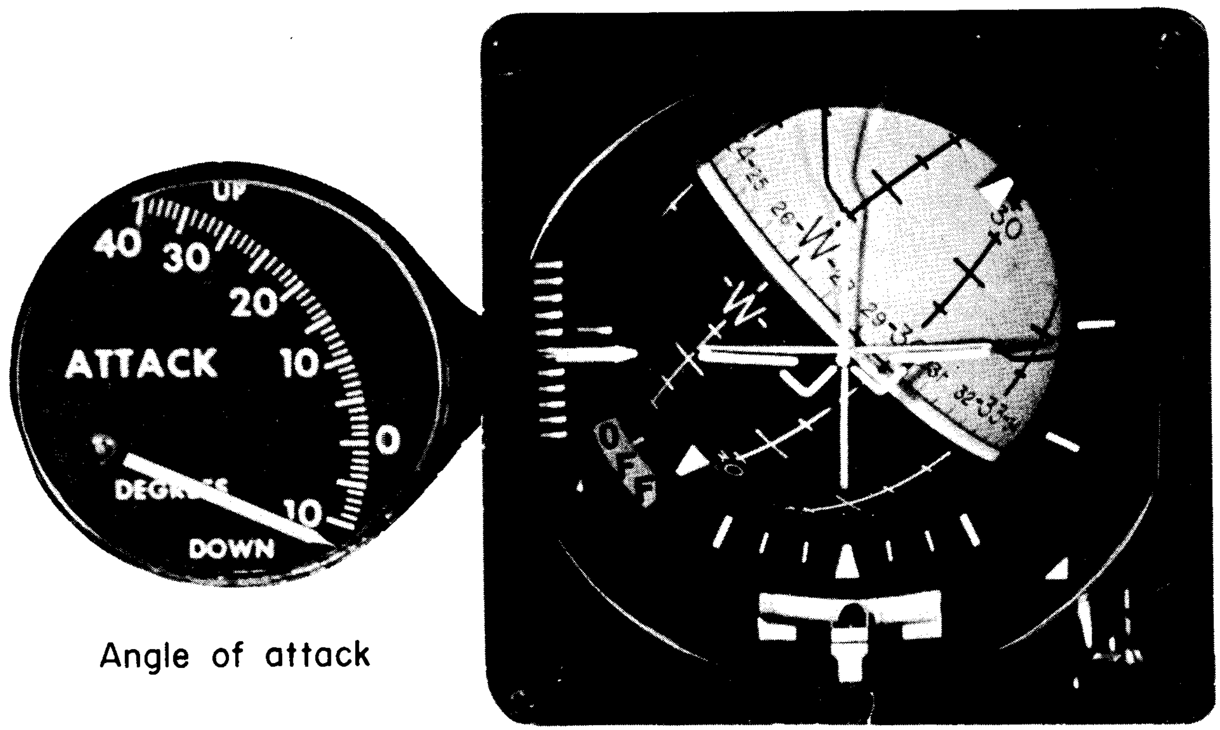


Figure 3.- X-15 cockpit.



Angle of attack

Airplane attitude three-axis ball

Figure 4.- X-15 airplane attitude display.

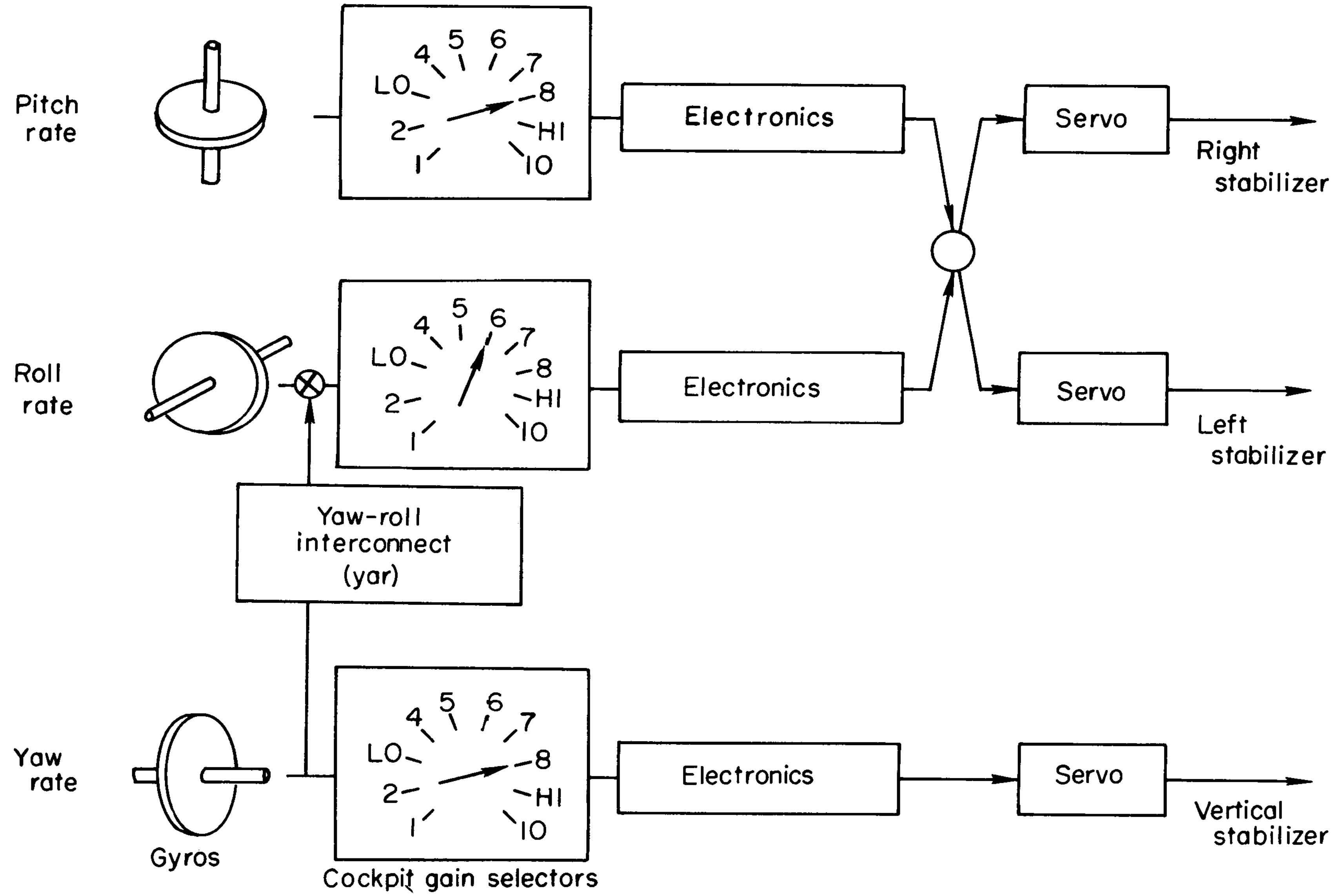


Figure 5.- Functional diagram of the X-15 stability augmentation system.

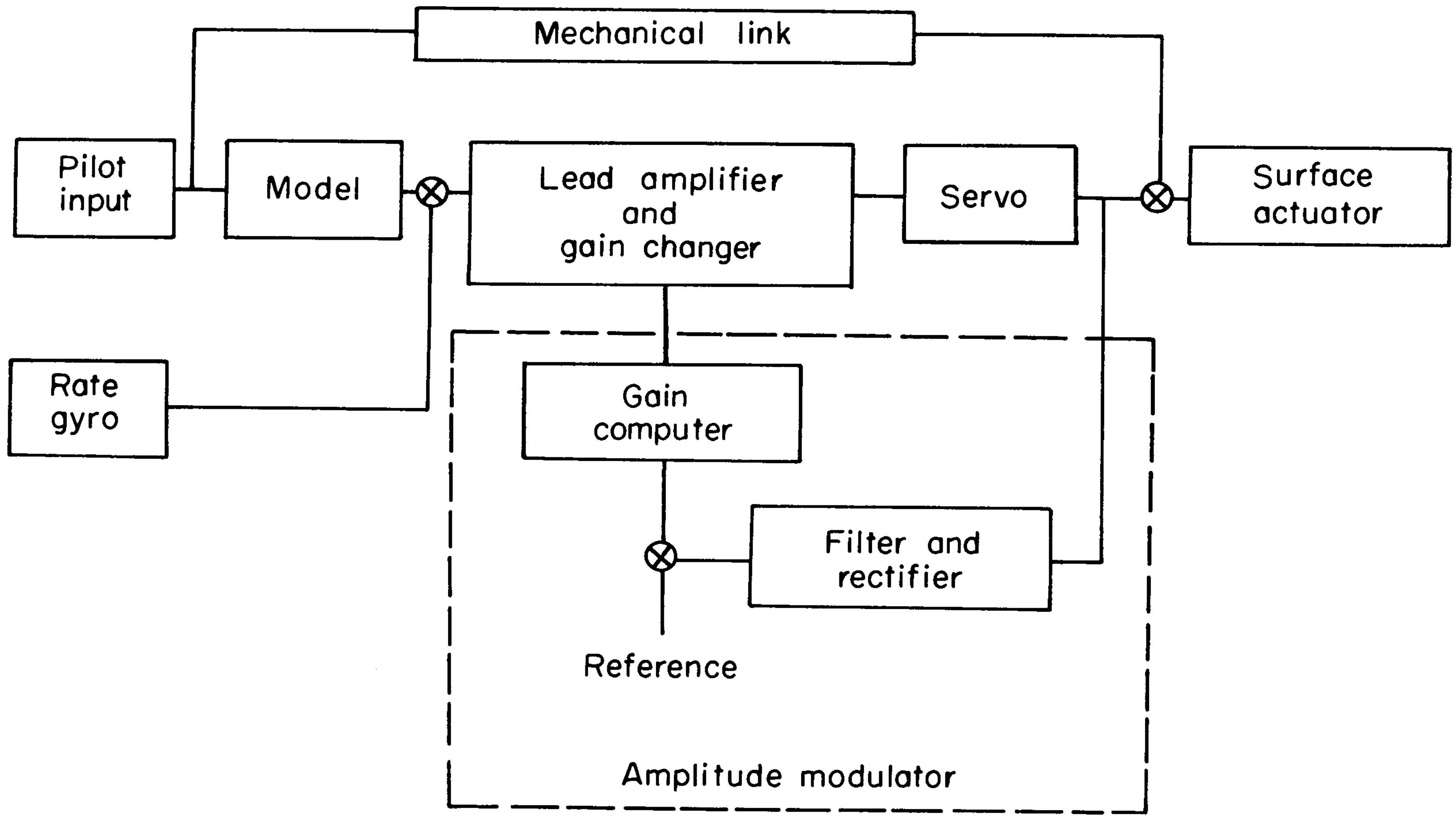


Figure 6.- MH-96 adaptive-control-system concept.

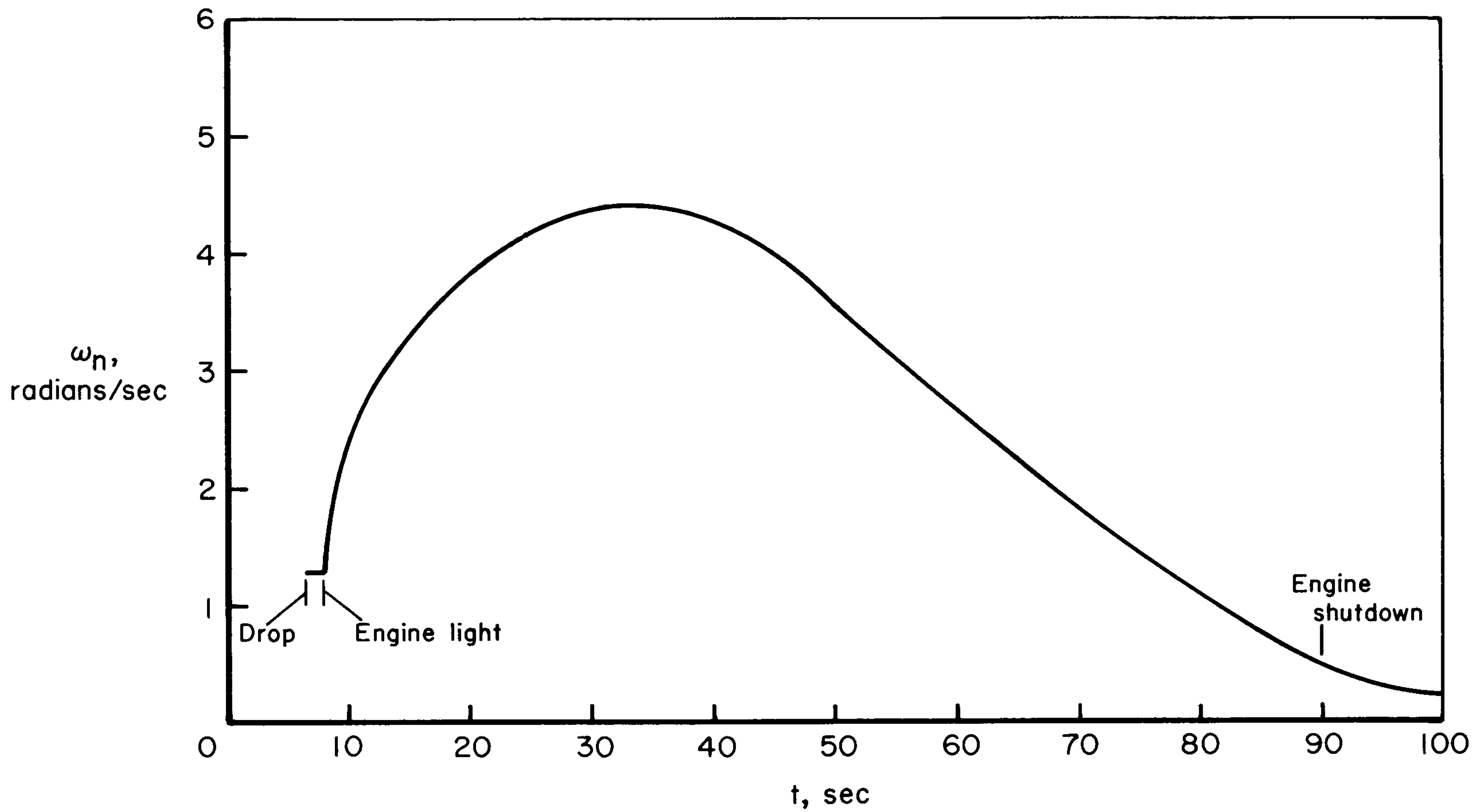


Figure 7.- X-15 longitudinal stability during a typical boost to a maximum altitude of 250,000 feet. Basic configuration without augmentation.

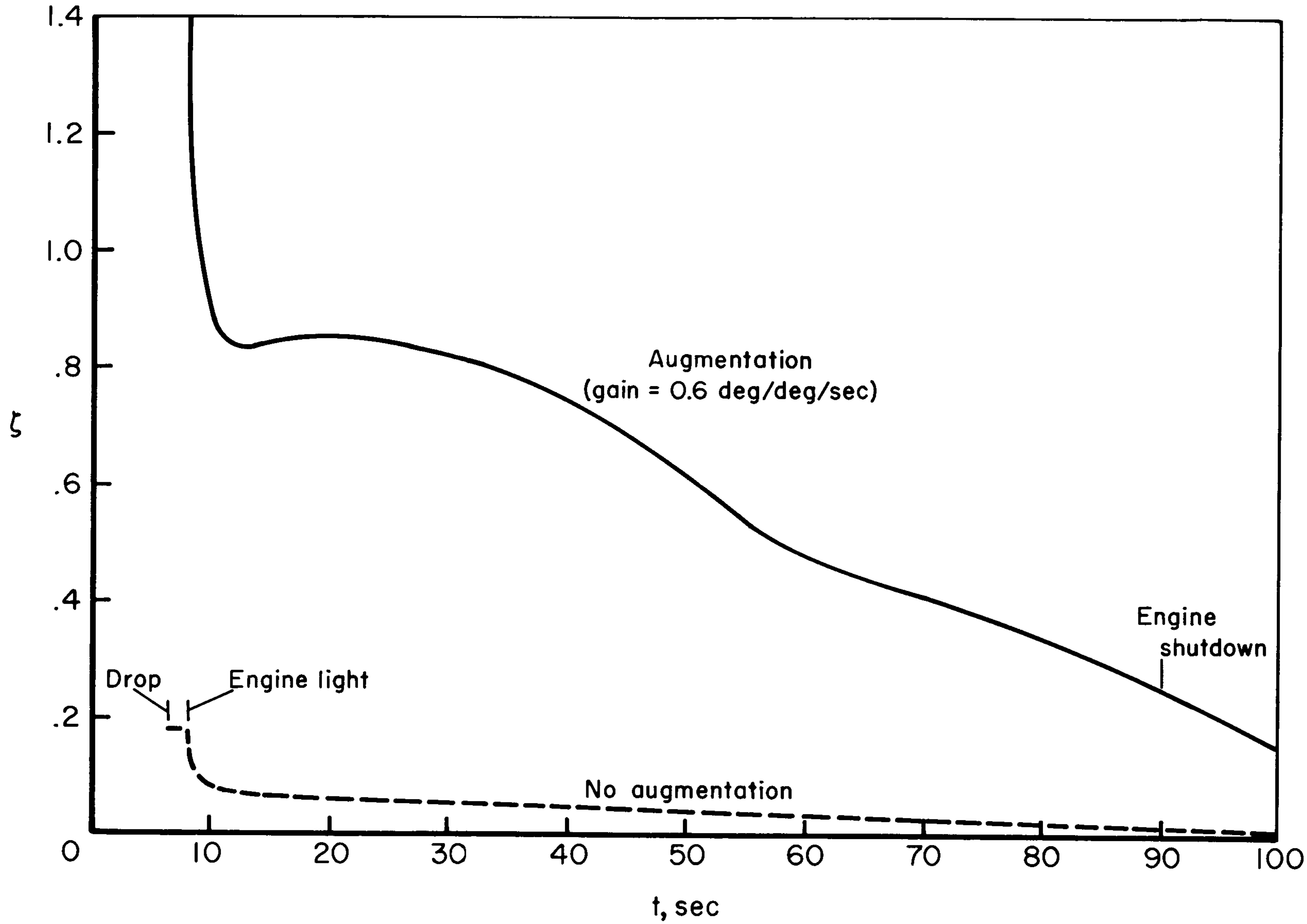


Figure 8.- X-15 longitudinal damping during a typical boost to a maximum altitude of 250,000 feet. Basic configuration.

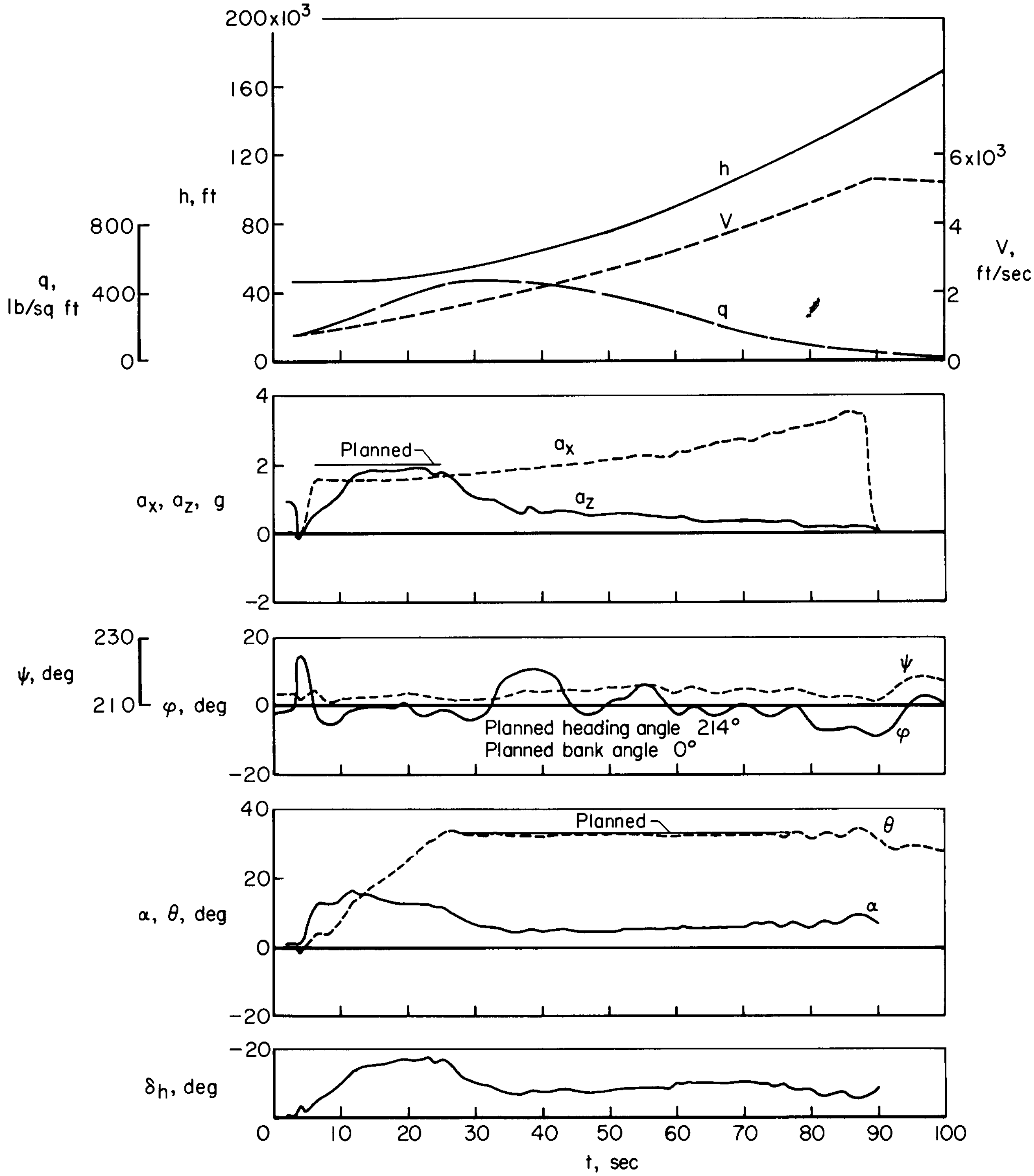


Figure 9.- Typical X-15 launch with the stability augmentation system to a maximum altitude of 226,400 feet; 100-percent thrust. Planned burnout conditions: t_b = 81 sec, V_{max} = 5,200 ft/sec, $h_{(a_x=0)}$ = 131,000 ft.

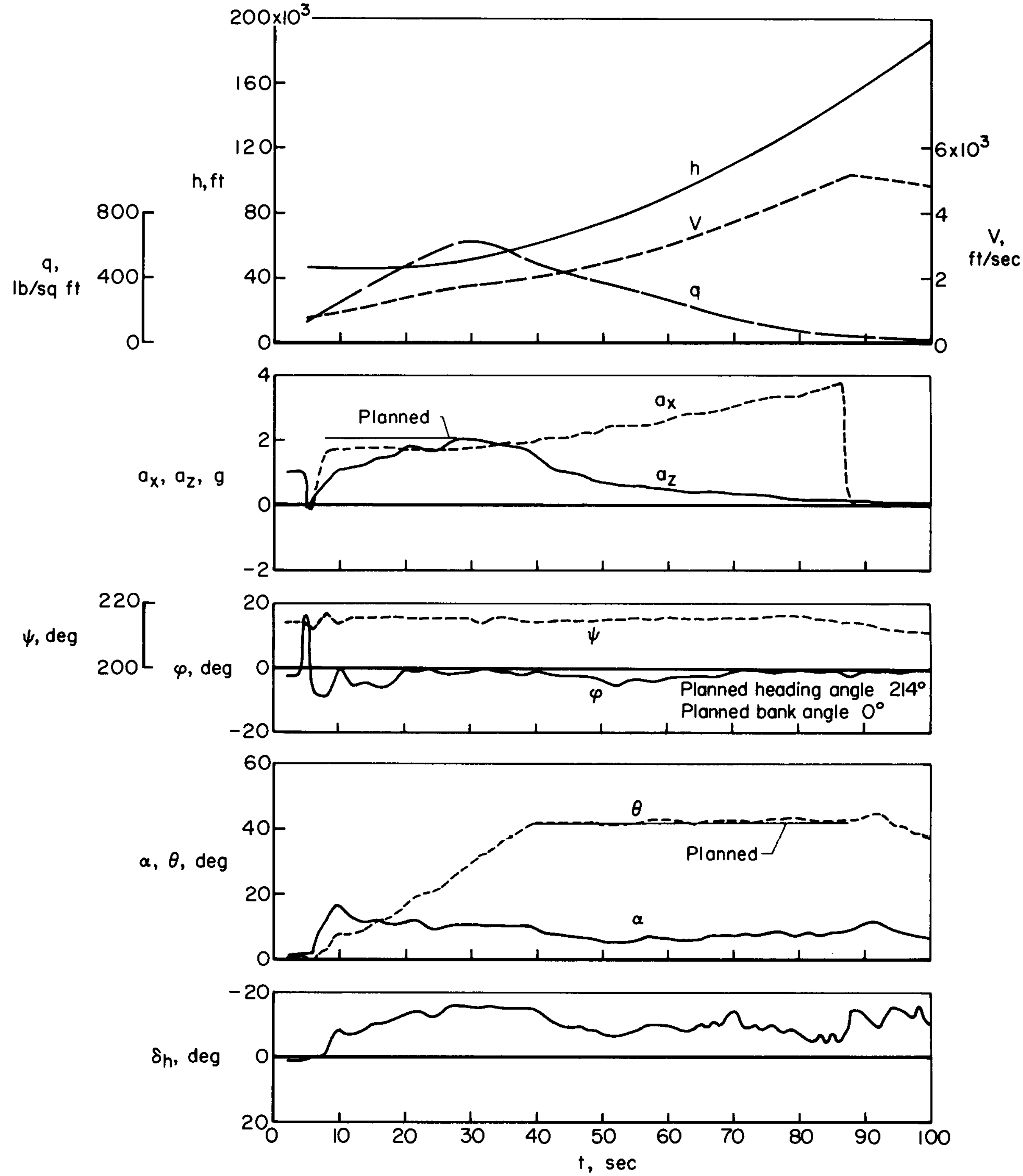


Figure 10.- Typical X-15 launch with the adaptive control system (φ and θ hold) to a maximum altitude of 285,000 feet; 100-percent thrust. Planned burnout conditions: t_b = 79 sec, V_{max} = 5,100 ft/sec, $h_{(a_x=0)}$ = 150,000 ft.

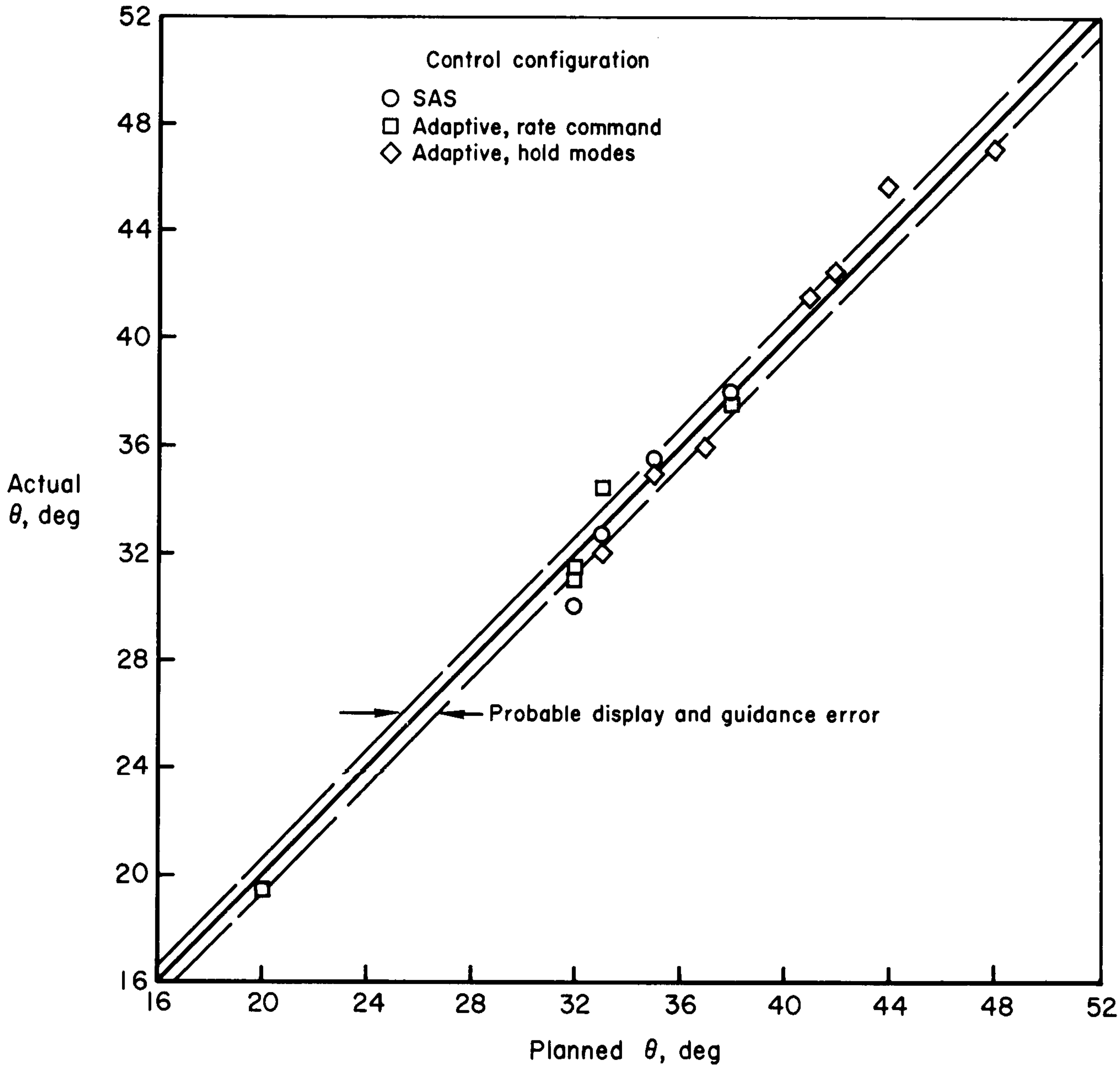


Figure 11.- Comparison of actual (average) and planned pitch angle during X-15 boost.

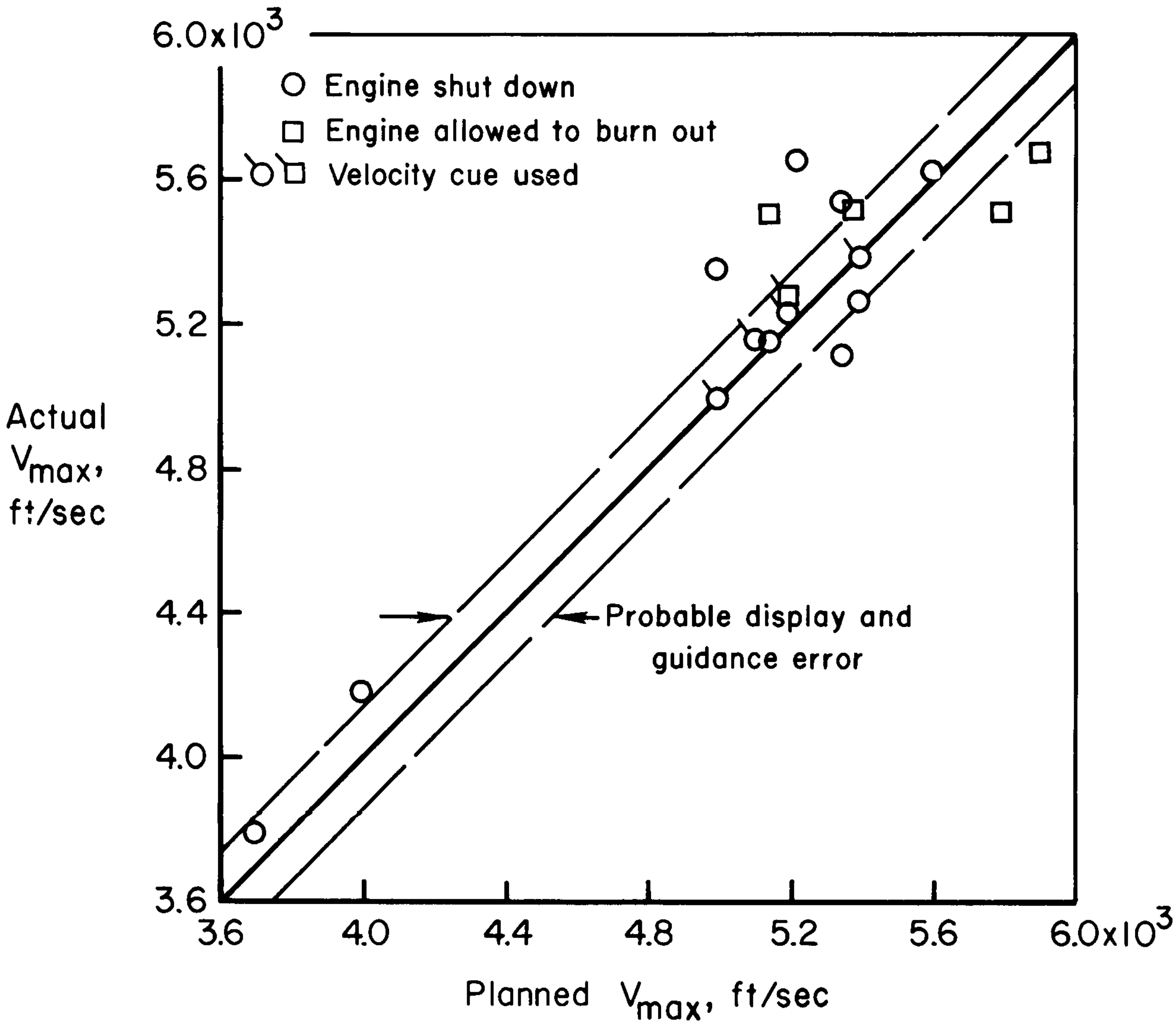
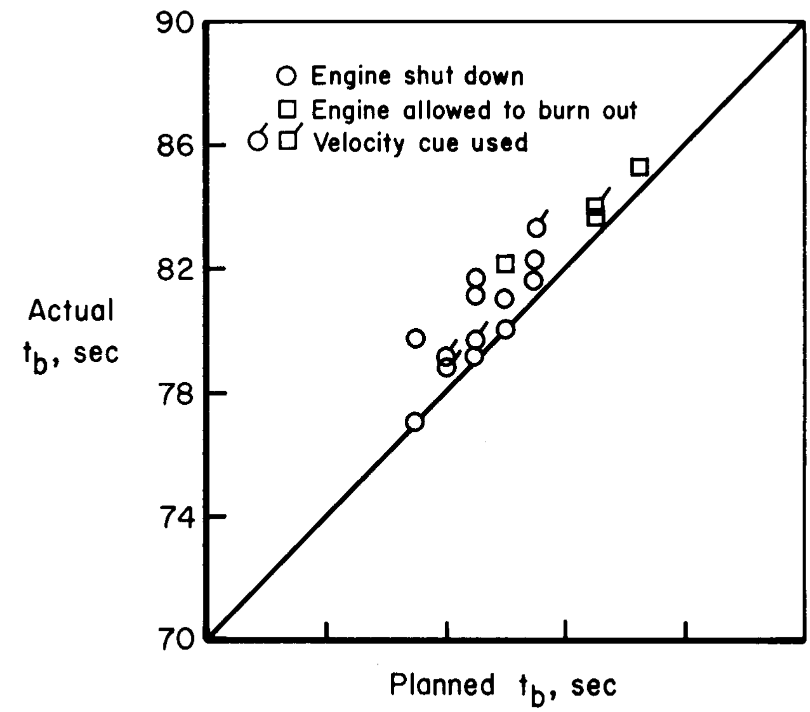
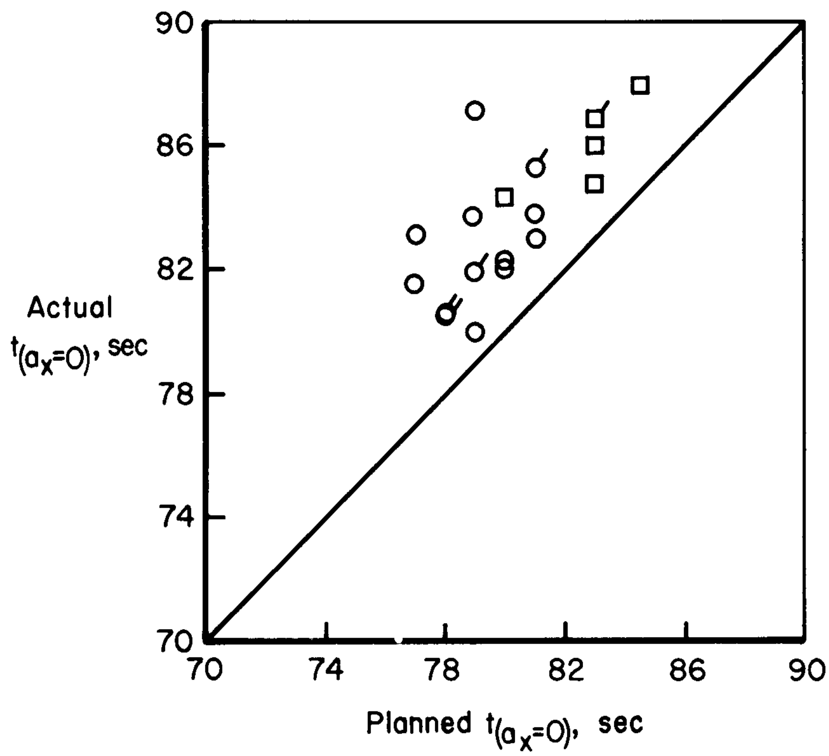


Figure 12.- Comparison of actual and planned maximum velocities.



(a) Time of reduced thrust (pilot's shutdown).



(b) Time to zero longitudinal acceleration.

Figure 13.- Comparison of actual and planned burning times.

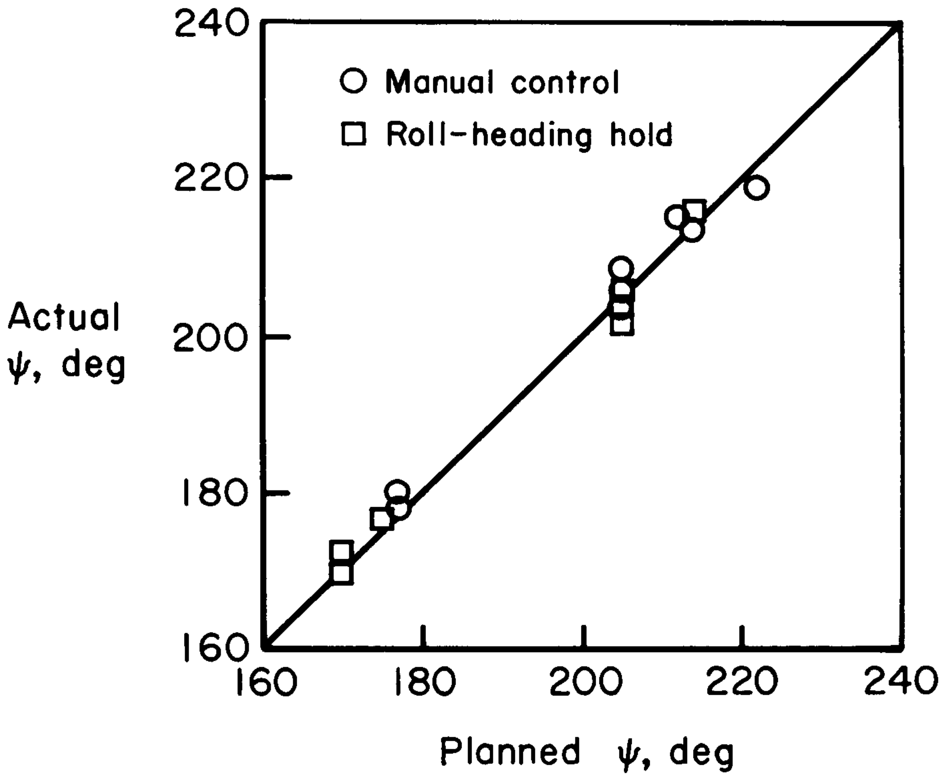


Figure 14.- Comparison of actual and planned heading.

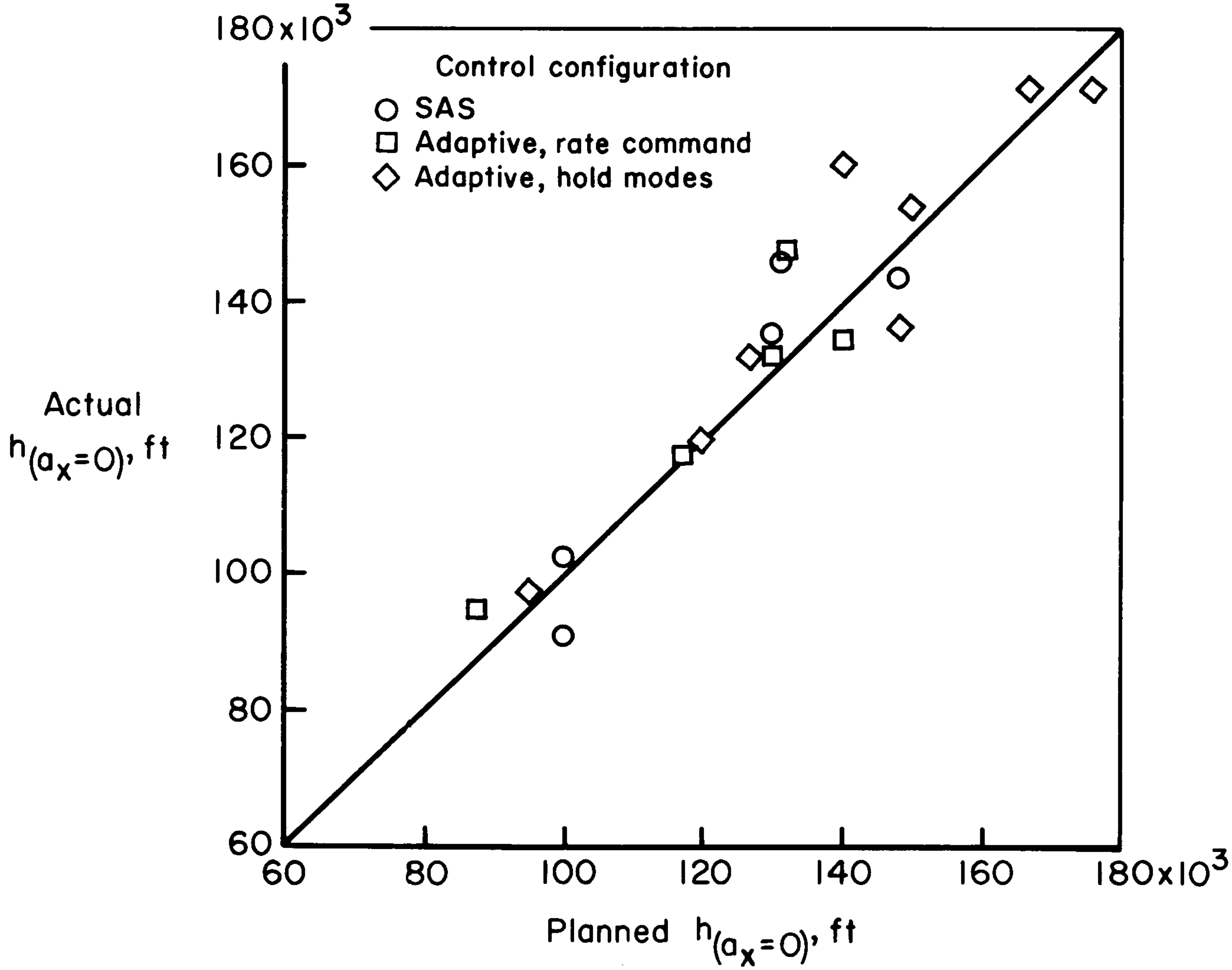


Figure 15.- Comparison of actual and planned altitude at engine shutdown.

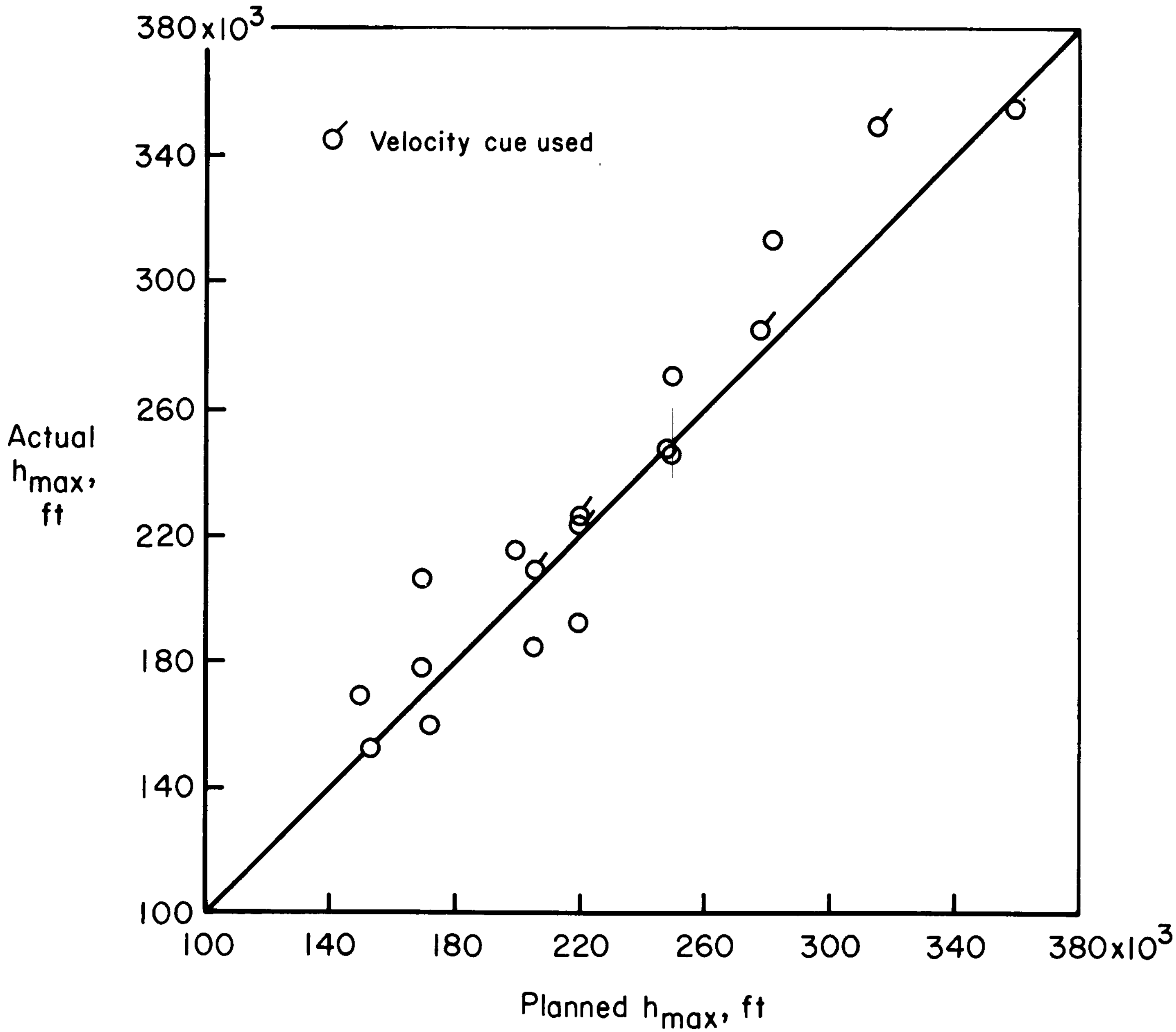


Figure 16.- Comparison of actual and planned maximum altitude.

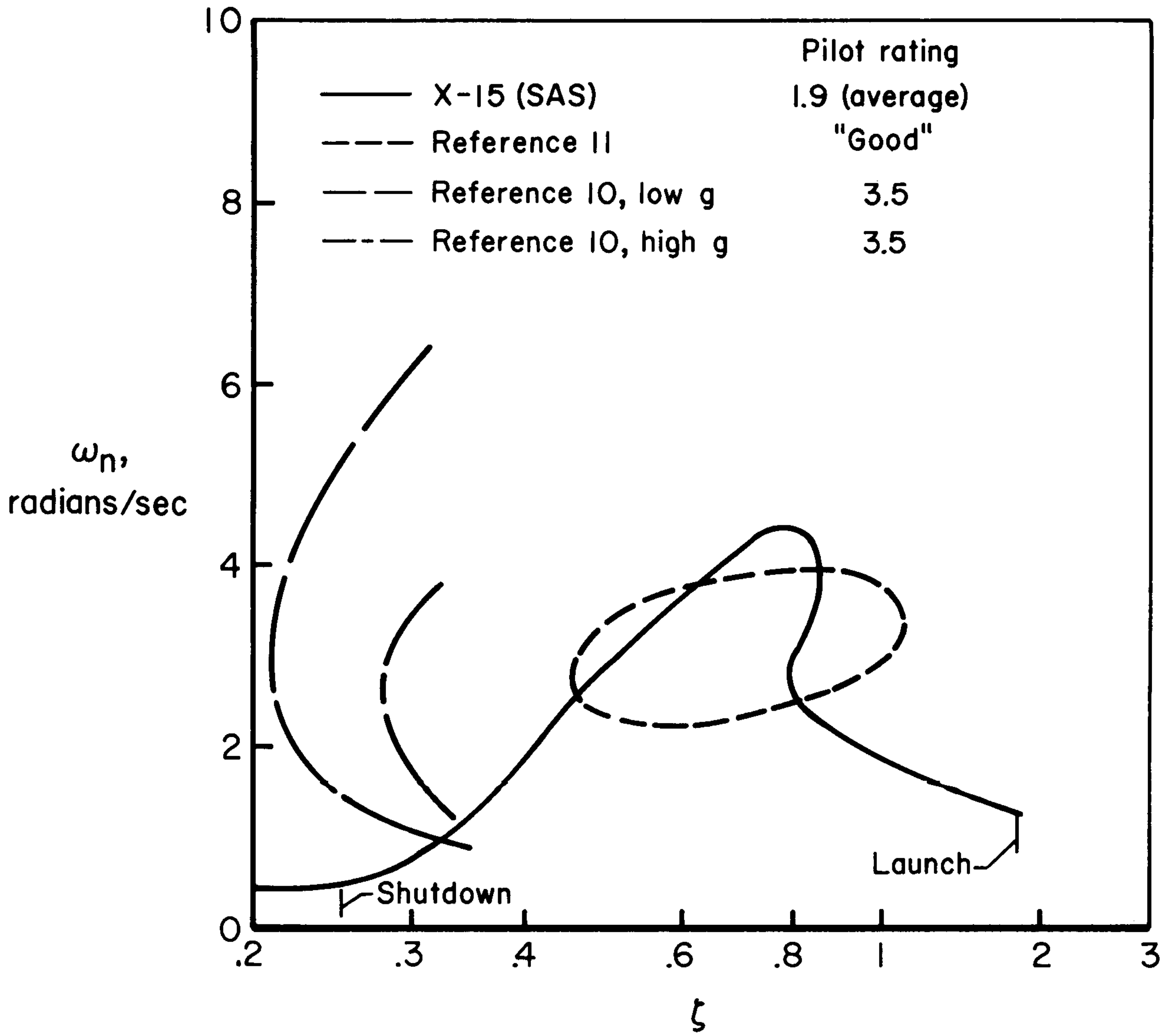
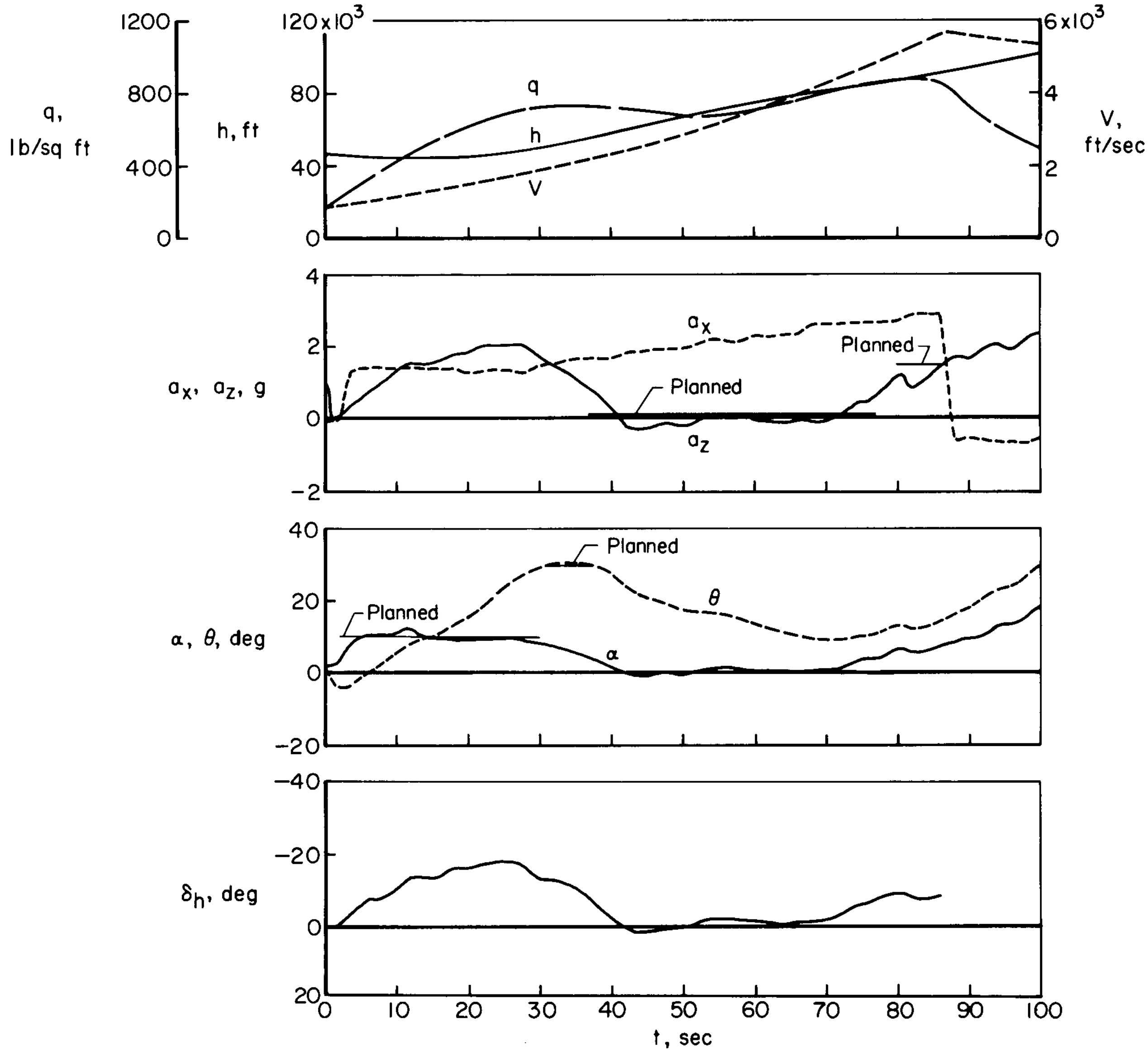
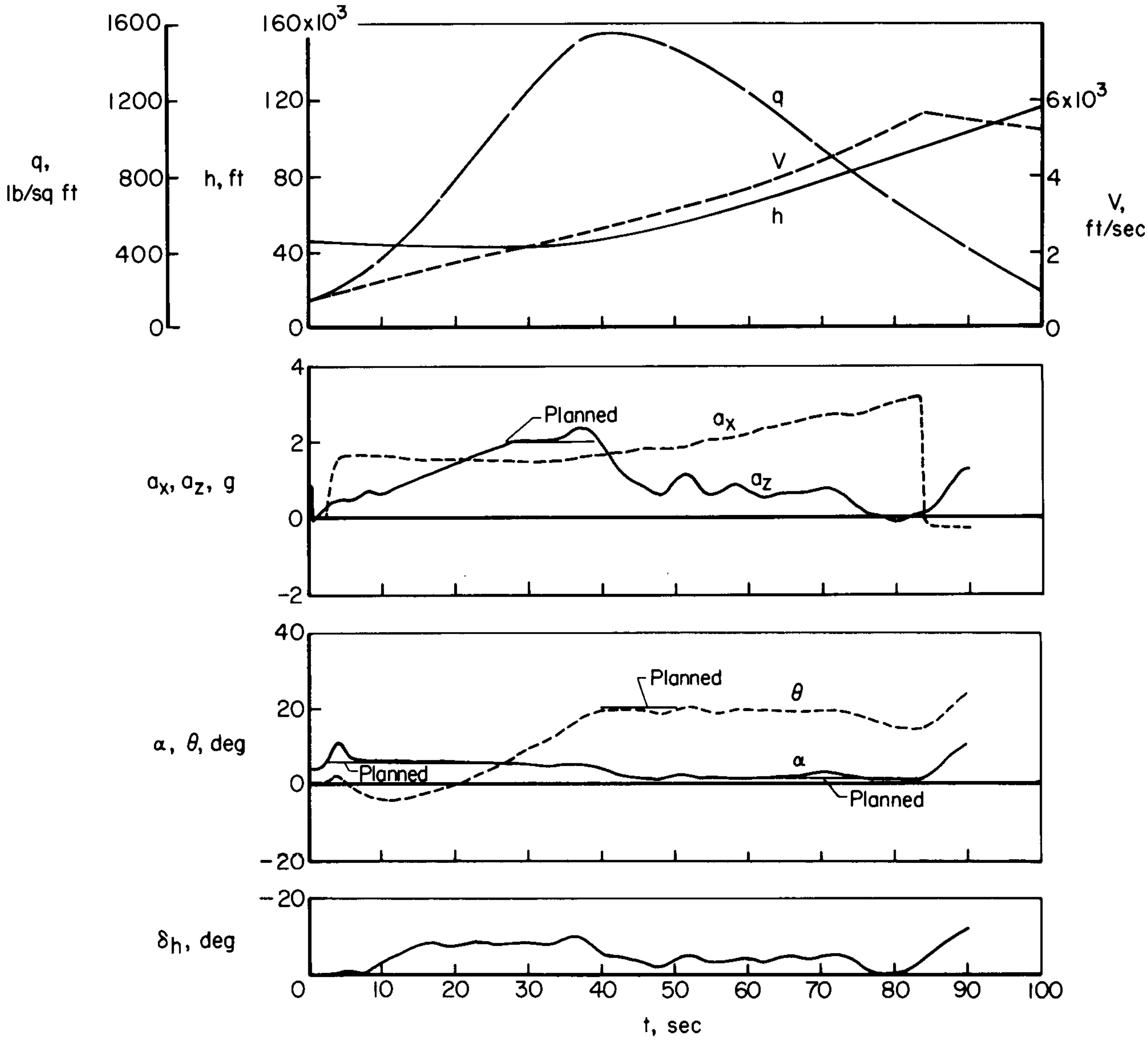


Figure 17.- Comparison of pilot rating of X-15 boost and referenced piloting tasks (longitudinal).



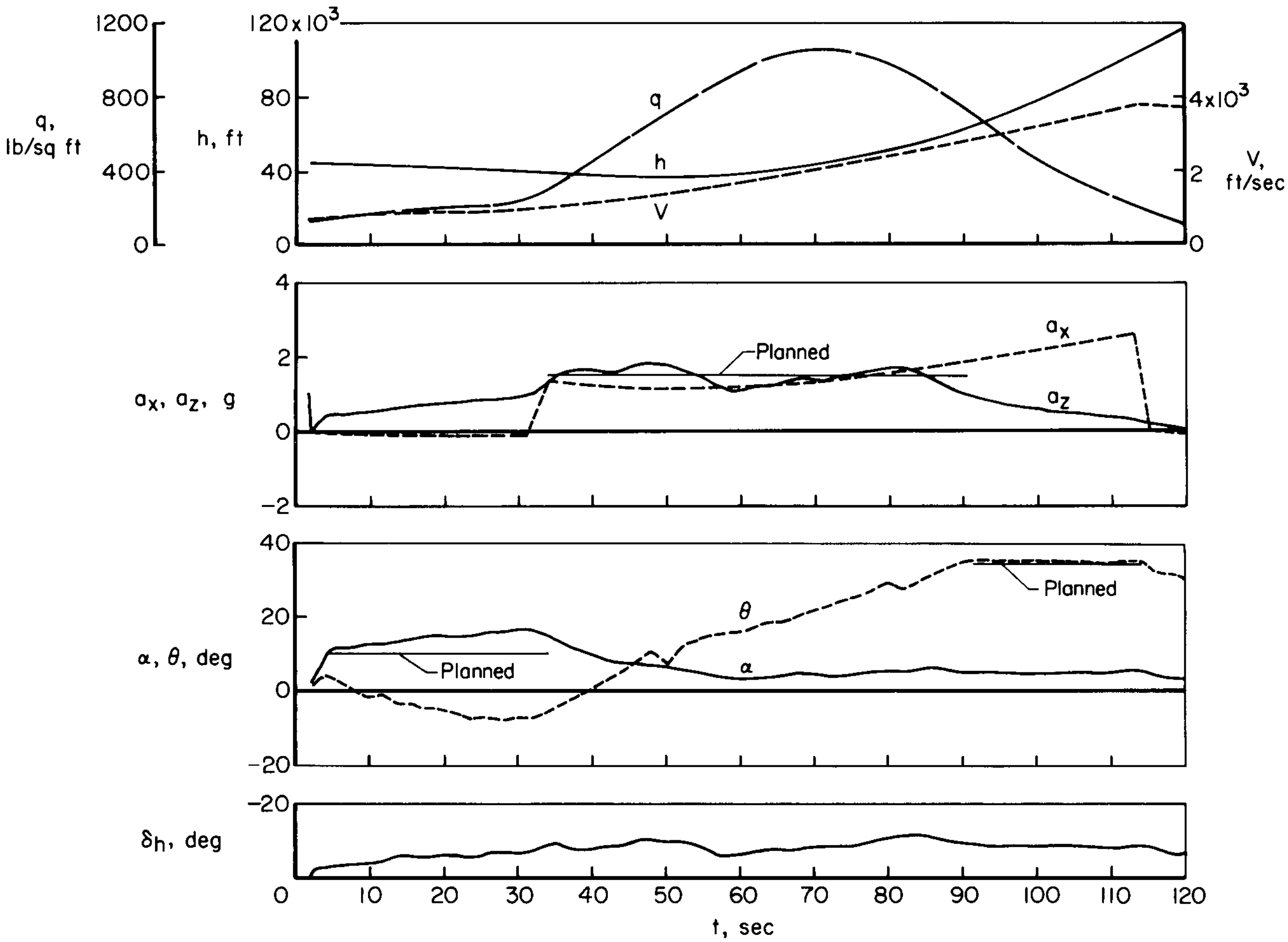
(a) h_{max} = 154,000 ft; basic X-15; SAS; 100-percent thrust. Planned burnout conditions: t_b = 83 sec, V_{max} = 5,900 ft/sec, $h_{(a_x=0)}$ = 100,000 ft.

Figure 18.- X-15 boosts to high altitude.



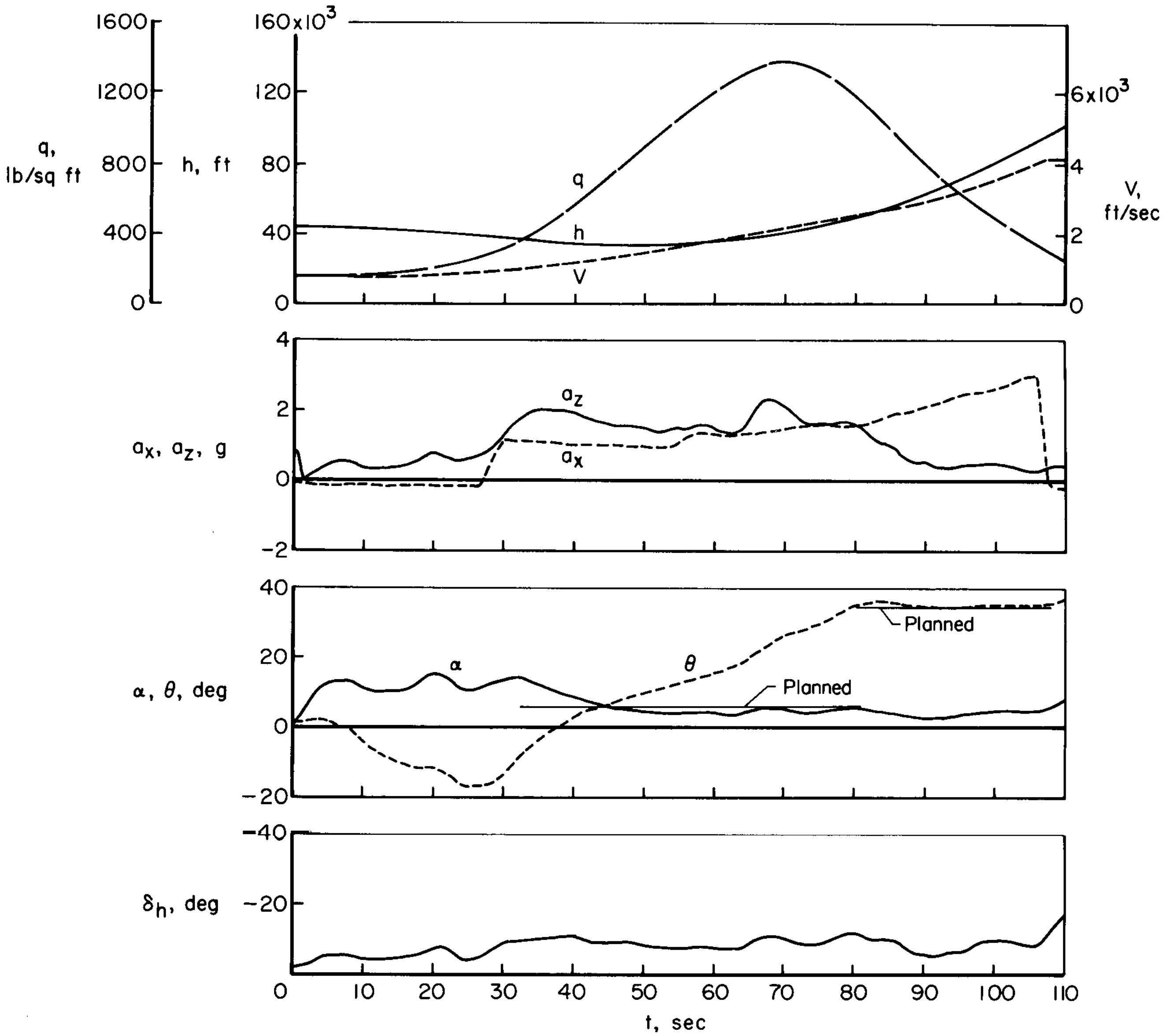
(b) h_{max} = 160,000 ft; ventral off; adaptive control system (rate command); 100-percent thrust. Planned burnout conditions: t_b = 80 sec, V_{max} = 5,600 ft/sec, $h_{(a_x=0)}$ = 87,000 ft.

Figure 18.- Continued.



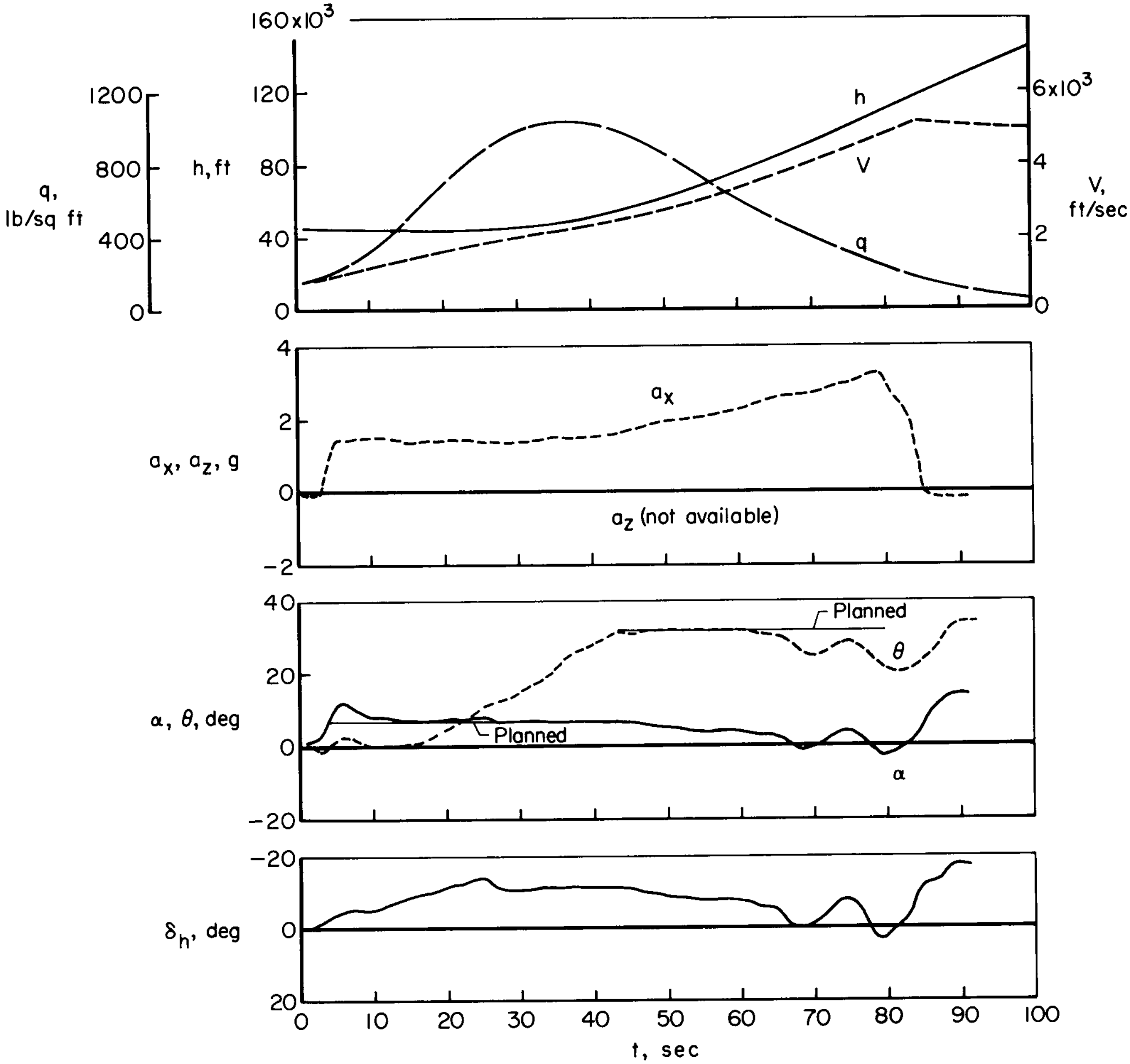
(c) h_{max} = 170,000 ft; basic X-15; SAS; 75-percent thrust. Planned burnout conditions: t_b = 79 sec, V_{max} = 3,700 ft/sec, $h_{(a_x=0)}$ = 100,000 ft.

Figure 18.- Continued.



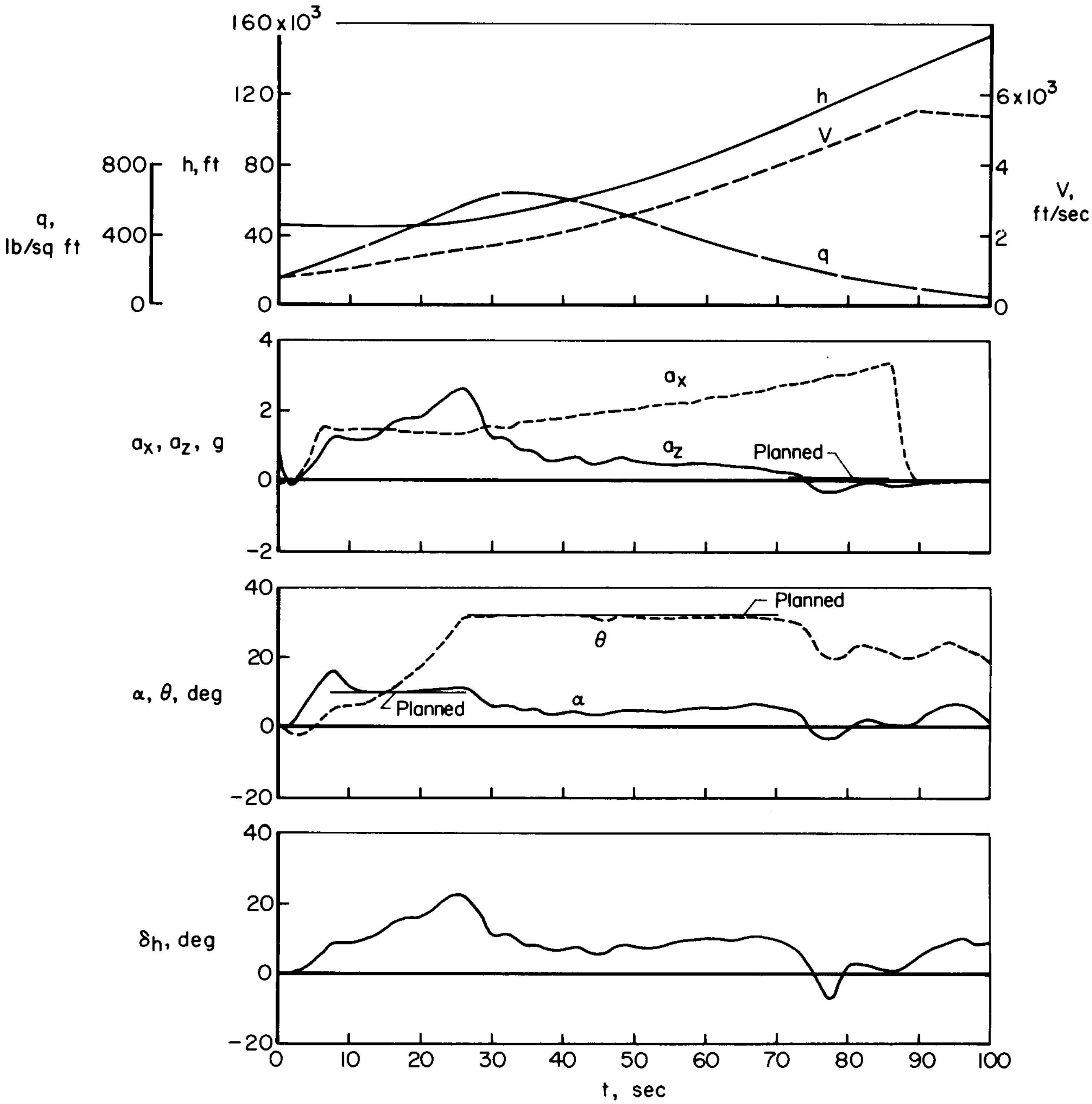
(d) h_{max} = 180,000 ft; adaptive control system (θ hold); basic X-15; 100-percent thrust. Planned burnout conditions: t_b = 79 sec, V_{max} = 4,000 ft/sec, $h_{(a_x=0)}$ = 95,000 ft.

Figure 18.- Continued.



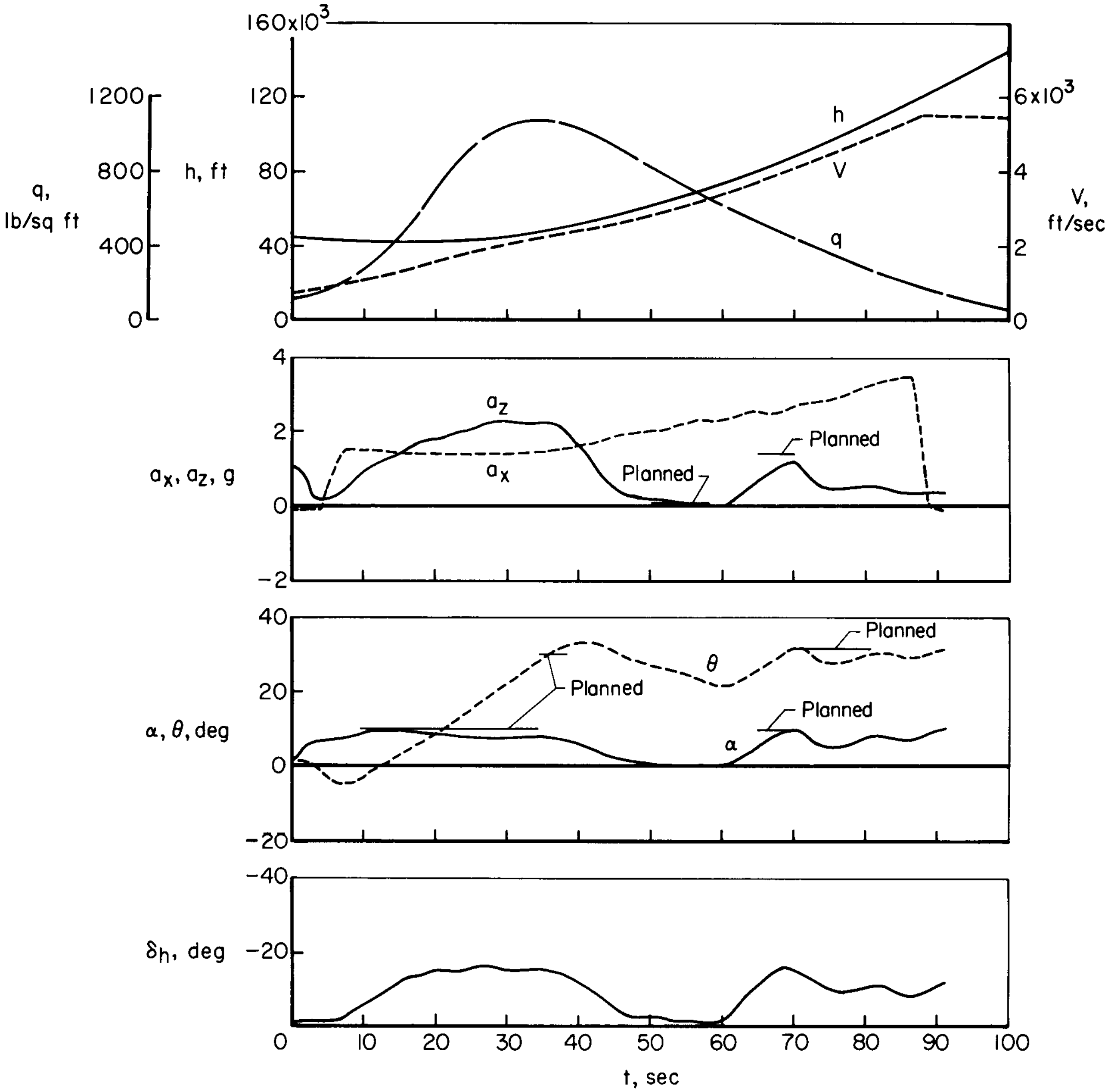
(e) h_{max} = 184,600 ft; basic X-15; adaptive control system (rate command); 100-percent thrust. Planned burnout conditions: t_b = 77 sec, V_{max} = 5,150 ft/sec, $h_{(a_x=0)}$ = 117,000 ft.

Figure 18.- Continued.



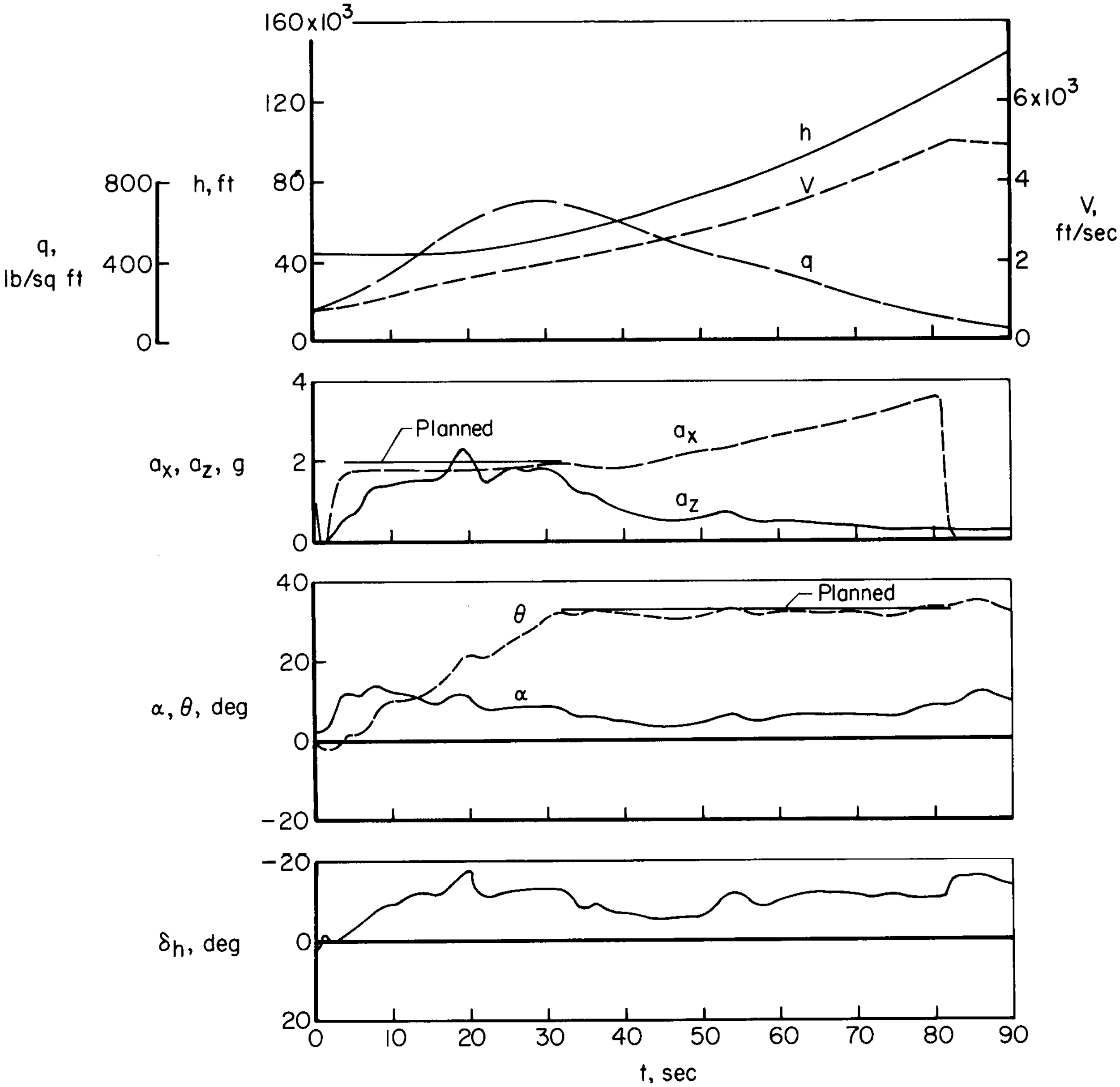
(f) h_{max} = 193,600 ft; basic X-15; adaptive control system (rate command); 100-percent thrust. Planned burnout conditions: t_b = 83 sec, V_{max} = 5,800 ft/sec, $h_{(a_x=0)}$ = 140,000 ft.

Figure 18.- Continued.



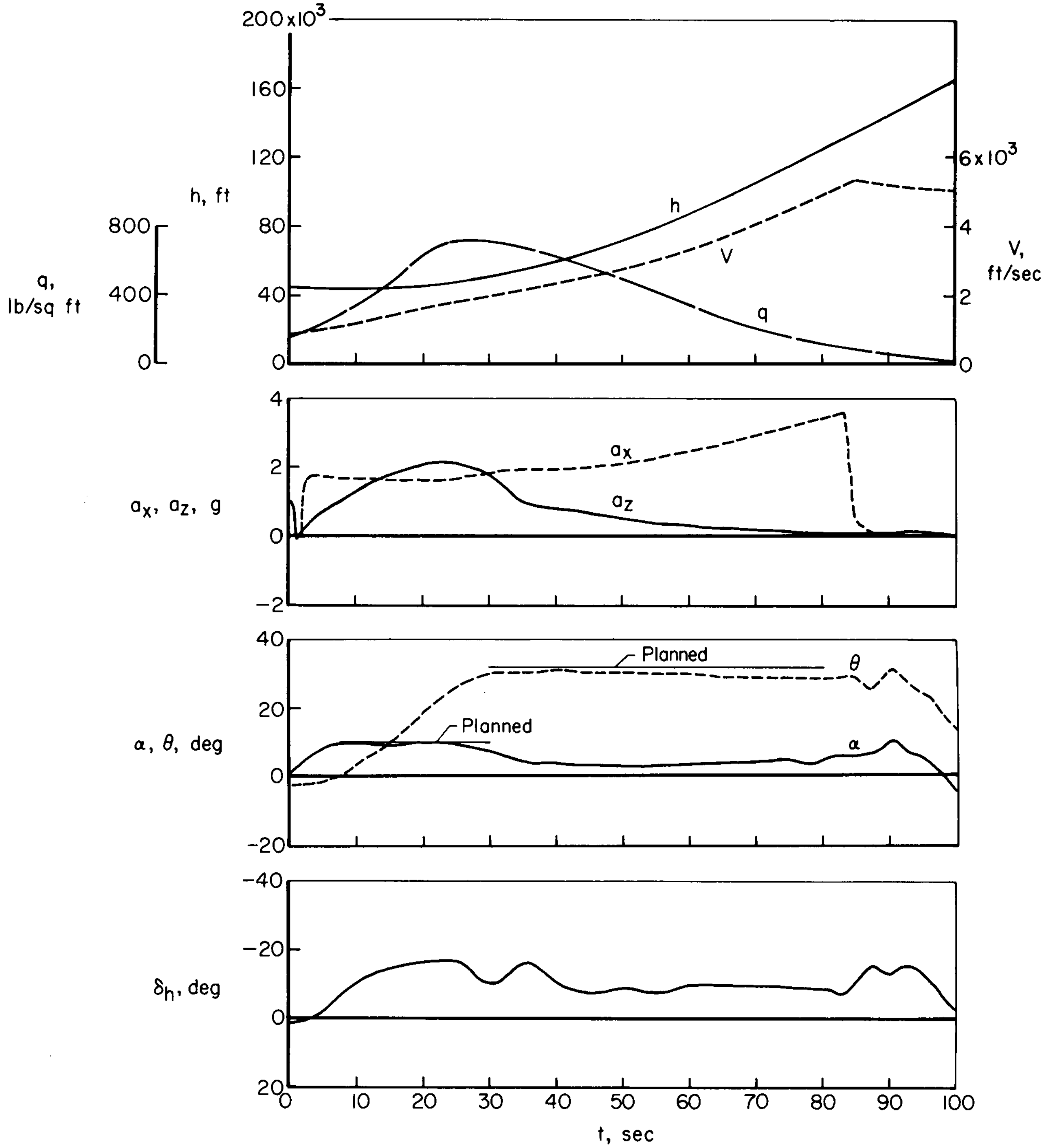
(g) h_{max} = 207,500 ft; basic X-15; adaptive control system (φ and α hold); 100-percent thrust. Planned burnout conditions: t_b = 81 sec, V_{max} = 5,350 ft/sec, $h_{(a_x=0)}$ = 120,000 ft.

Figure 18.- Continued.



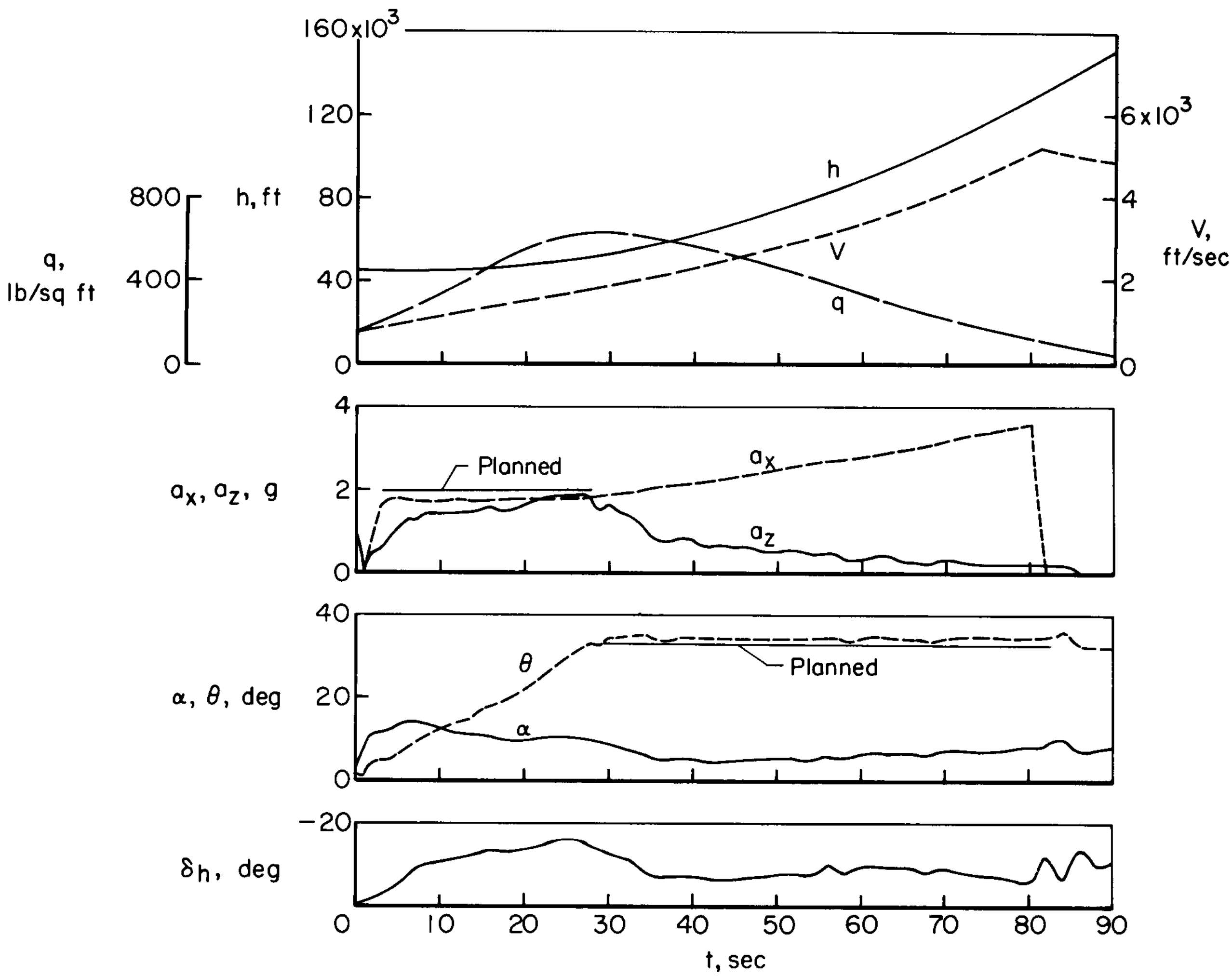
(h) h_{max} = 209,400 ft; ventral off; adaptive control system (φ hold); 100-percent thrust. Planned burnout conditions: t_b = 78 sec, V_{max} = 5,000 ft/sec, $h_{(a_x=0)}$ = 127,000 ft.

Figure 18.- Continued.



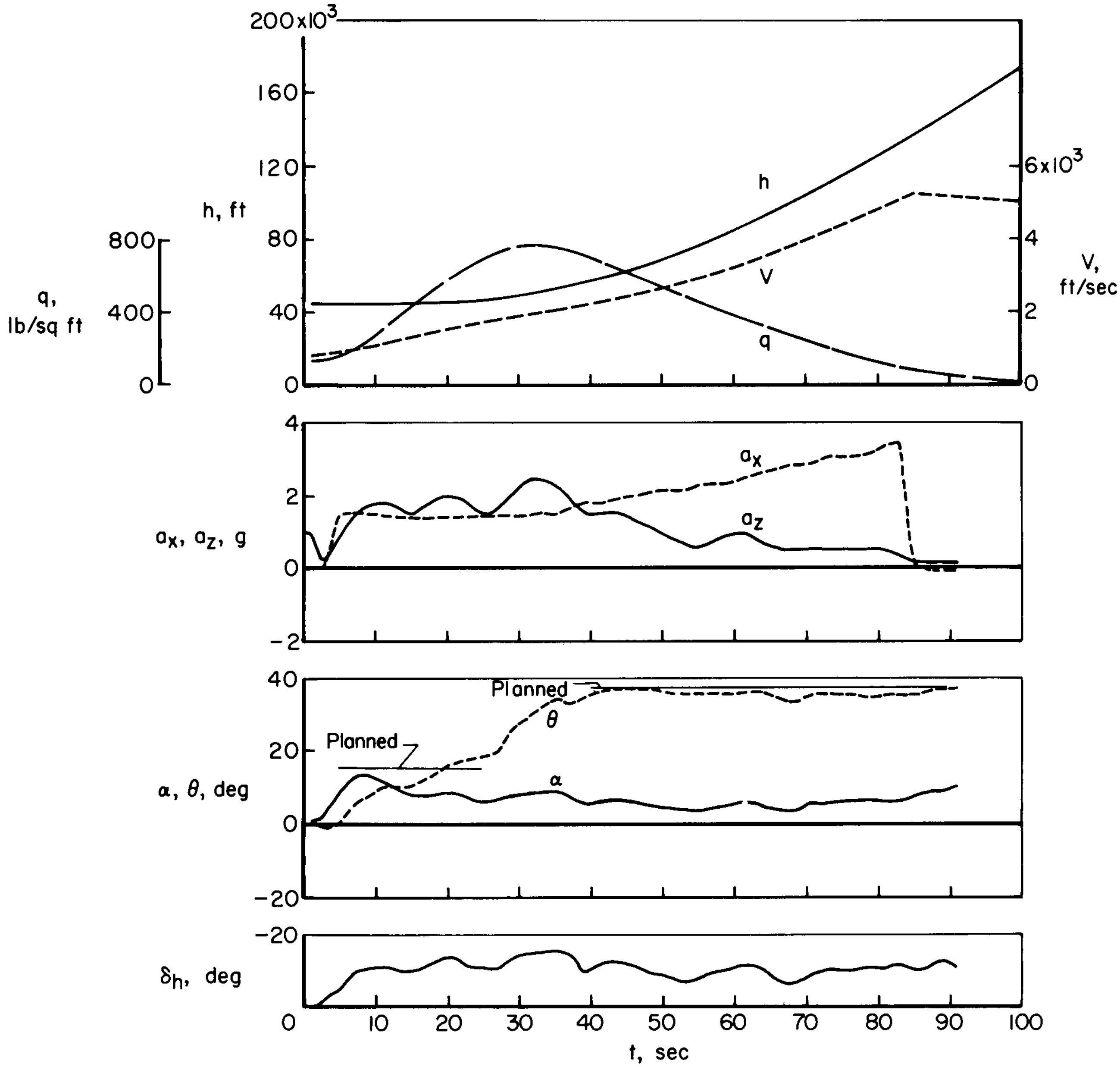
(i) h_{max} = 217,000 ft; basic X-15; SAS; 100-percent thrust. Planned burnout conditions: t_b = 79 sec, V_{max} = 5,000 ft/sec, $h_{(a_x=0)}$ = 130,000 ft.

Figure 18.- Continued.



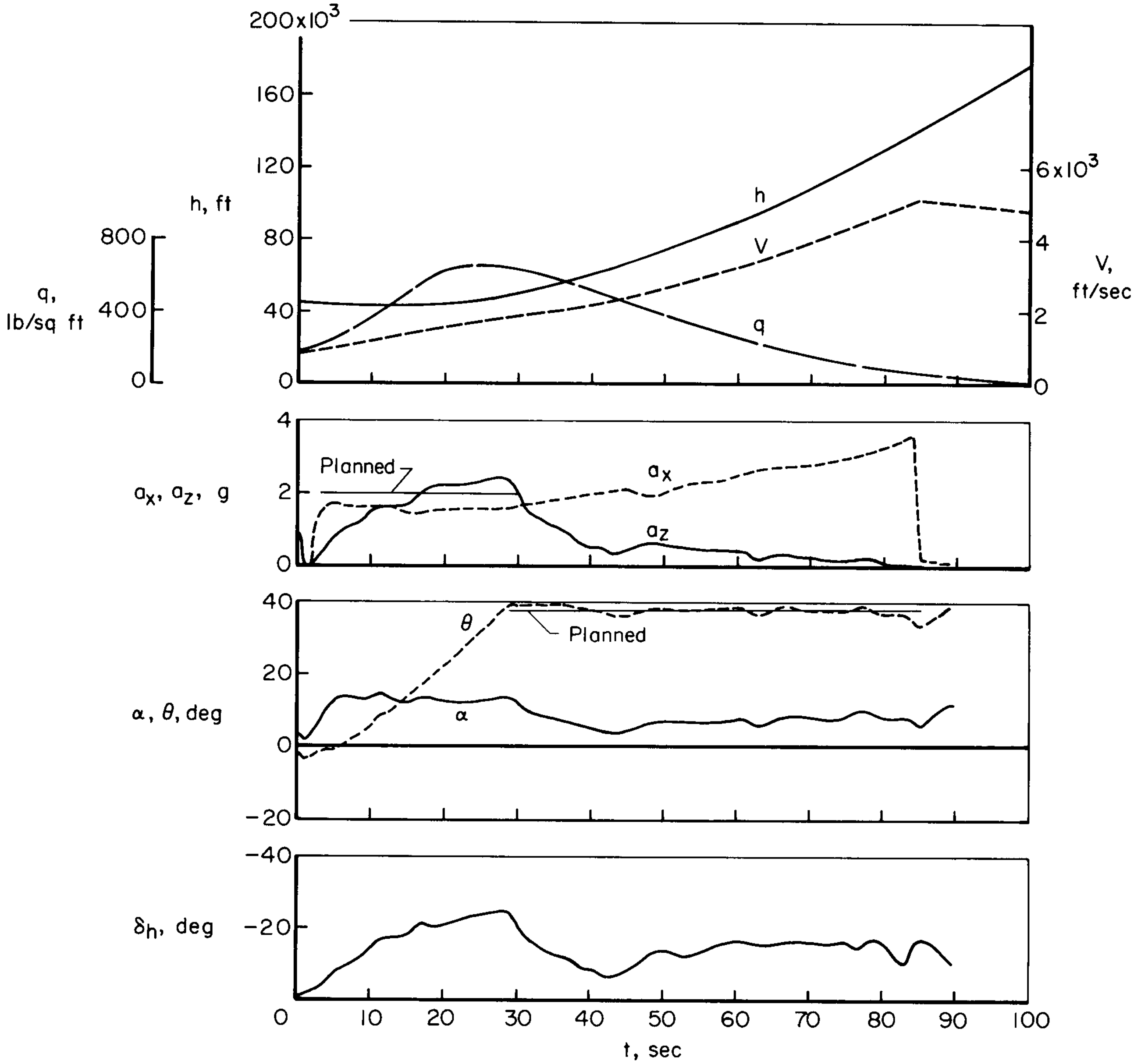
(j) h_{max} = 223,700 ft; ventral off; adaptive control system (rate command); 100-percent thrust. Planned burnout conditions: t_b = 78 sec, V_{max} = 5,200 ft/sec, $h_{(a_x=0)}$ = 130,000 ft.

Figure 18.- Continued.



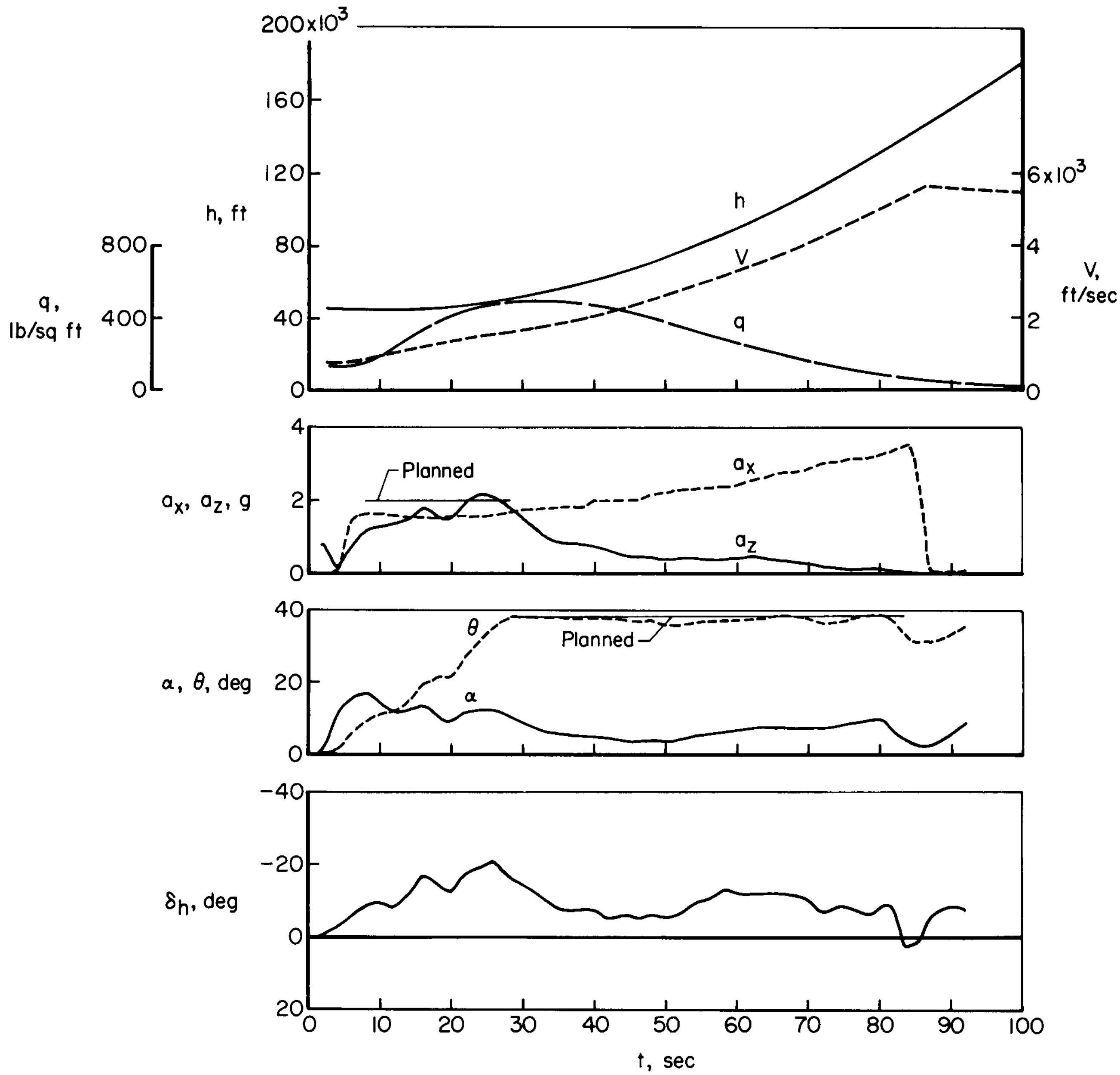
(k) h_{max} = 246,700 ft; basic X-15; adaptive control system (φ and θ hold); 100-percent thrust. Planned burnout conditions: t_b = 80 sec, V_{max} = 5,400 ft/sec, $h_{(a_x=0)}$ = 148,000 ft.

Figure 18.- Continued.



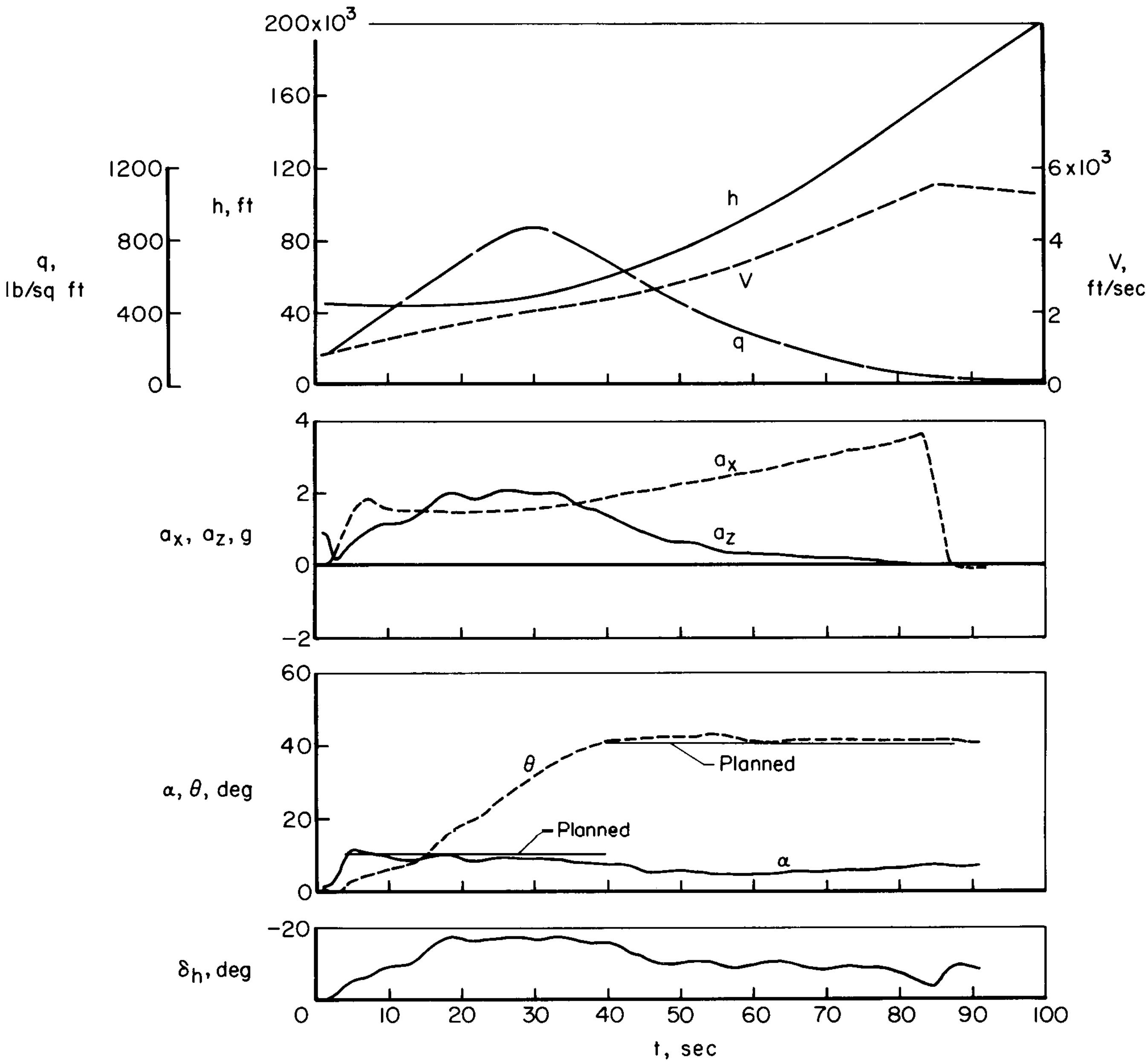
(l) h_{max} = 247,000 ft; basic X-15; SAS; 100-percent thrust. Planned burnout conditions: t_b = 81 sec, V_{max} = 5,350 ft/sec, $h_{(a_x=0)}$ = 148,000 ft.

Figure 18.- Continued.



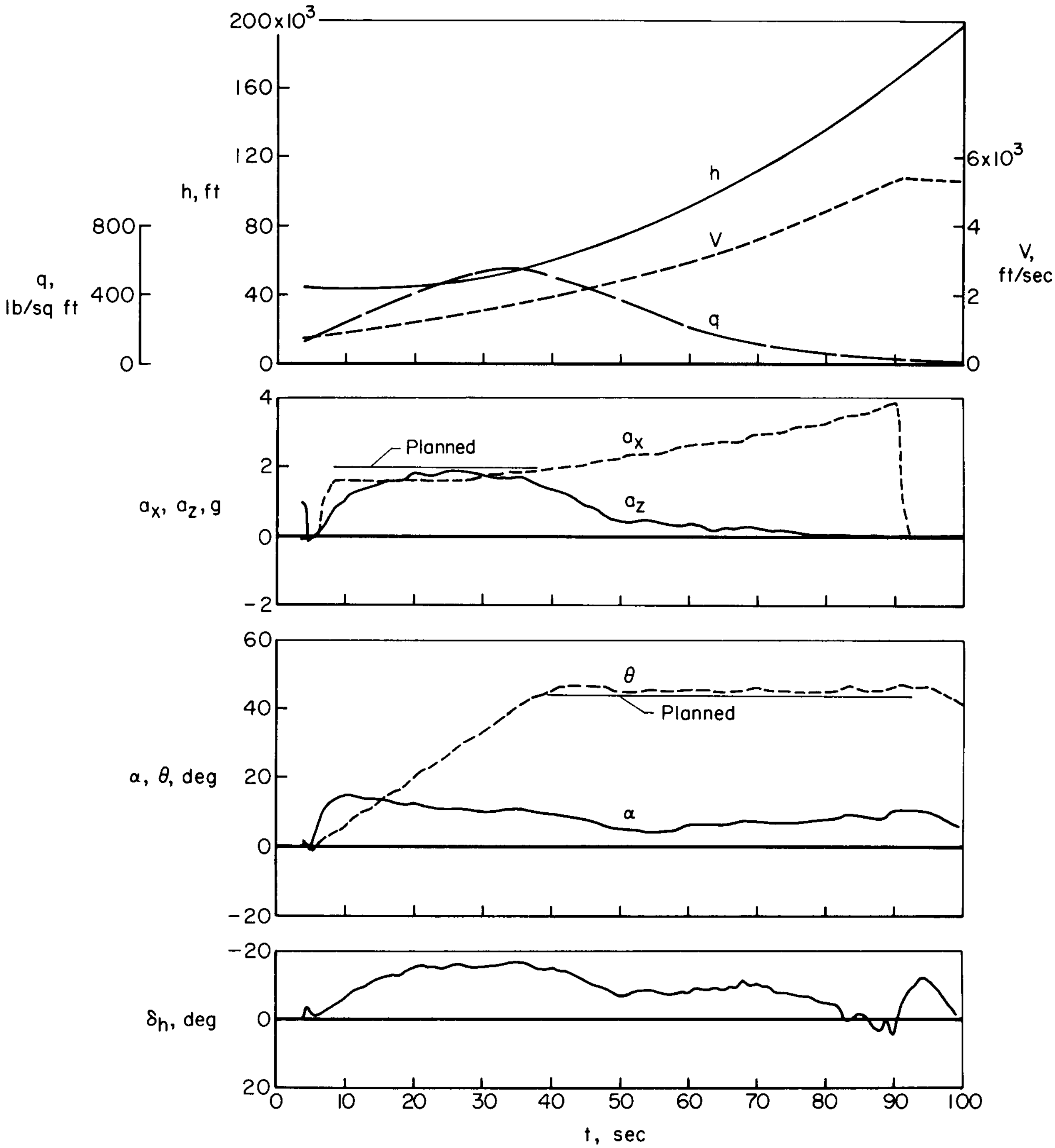
(m) h_{max} = 271,700 ft; ventral off; adaptive control system (rate command); 100-percent thrust. Planned burnout conditions: t_b = 77 sec, V_{max} = 5,220 ft/sec, $h_{(a_x=0)}$ = 132,000 ft.

Figure 18.- Continued.



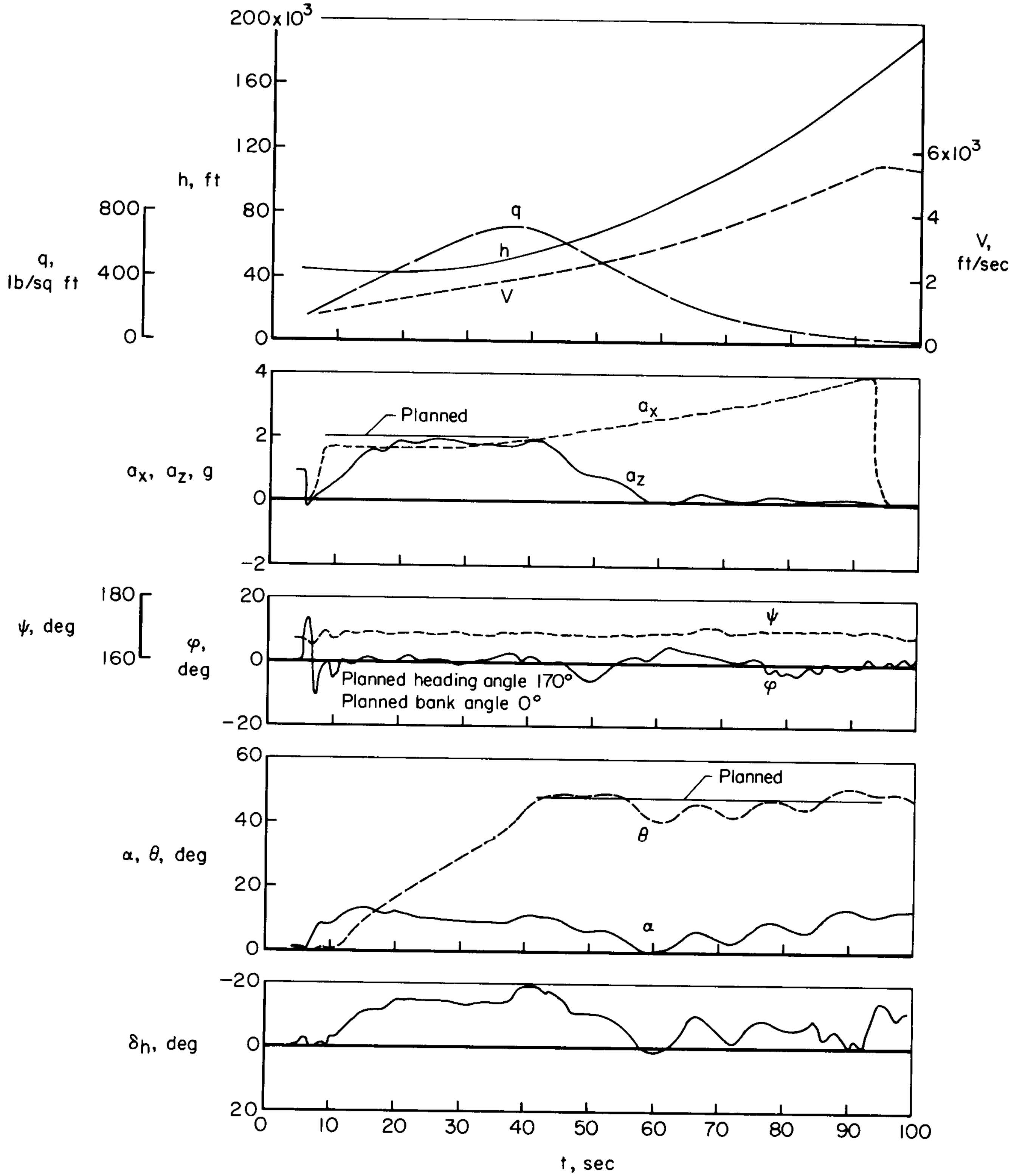
(n) h_{max} = 314,750 ft; basic X-15; adaptive control system (φ and θ hold); 100-percent thrust. Planned burnout conditions: t_b = 80 sec, V_{max} = 5,150 ft/sec, $h_{(a_x=0)}$ = 140,000 ft.

Figure 18.- Continued.



(o) h_{max} = 347,800 ft; ventral off; adaptive control system (φ hold); 100-percent thrust. Planned burnout conditions: t_b = 83 sec, V_{max} = 5,400 ft/sec, $h_{(a_x=0)}$ = 165,000 ft.

Figure 18.- Continued.



(p) h_{max} = 354,200 ft; ventral off; adaptive control system (φ hold); 100-percent thrust. Planned burnout conditions: t_b = 84.5 sec, V_{max} = 5,380 ft/sec, $h_{(a_x=0)}$ = 176,000 ft.

Figure 18.- Concluded.

NASA TN D-2289
National Aeronautics and Space Administration.
PILOTING PERFORMANCE DURING THE BOOST OF THE X-15 AIRPLANE TO HIGH ALTITUDE.
Euclid C. Holleman. April 1964. 53p. OTS price, $1.50. (NASA TECHNICAL NOTE D-2289)

During the X-15 altitude-buildup program, flights were made in which the boost-climbout phase was similar to the launch of the initial stage of multistage vehicles. These flights are analyzed in an attempt to better define the pilot's capability to control the boost phase of flight. Airplane attitude and performance were controlled to the limits of the accuracy of the displays provided. The boost acceleration had no effect on the piloting control task; however, two pilots had difficulty shutting down the engine because of the throttle location.

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